ECONOMIC GEOLOGY

AND THE

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ECONOMIC GEOLOGY

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METALLIC MELTING POINT AND ORE DEPOSITION

C. J. SULLIVAN

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ABSTRACT

If the chalcophile and siderophile metals are arranged in order of their melting points, they fall into temperature groups very similar to those found in ore deposits. The oxyphile (lithophile) metals are not so easily associated on the basis of melting point.

The minerals in which the sulfophile elements occur are characterized by metallic or covalent bonds, whereas the oxyphile elements occur in minerals in which ionic bonding predominates. It appears that, where metallic or covalent bonding is most important, the melting point of an element is an index of the temperature at which that element may begin to move or cease to move; possibly it is an index of the temperature at which appreciable dissociation of sulphides occurs, thus allowing atomic diffusion to take place.

The relationship appears to suggest an alternative to the "hydrothermal solution" theory of ore genesis.

Temperature zoning, metal associations and the degree of concentration of various metals in ore deposits as compared with the quantities of the metals present in the crust, are examined in relation to these facts and ideas.

The genesis of a number of well-known ore deposits is re-examined.

INTRODUCTION

THAT temperature is a factor in ore deposition has been recognized by most field investigators; the mobility of lead, zinc and cadmium under quite low temperature conditions is, in fact, one of the most intriguing features about the whole problem of ore genesis; and of equal interest is the fact that copper, gold and tin, for example, are apparently not mobile in the primary zone under such conditions.

Attempts to explain differences such as this in terms of solubility (12)[1] seem singularly unsuccesful and there are no data known to the writer which show that lead may be transported for great distances in cool solutions while the transport of copper, nickel and cobalt can occur only in hot solutions. The evidence available from the weathering of orebodies for example is quite the reverse.

It cannot be assumed either that vastly different types of "solutions" carry lead and copper respectively during a period of ore deposition. Thus, near an igneous stock intruding a body of limestone, it is common to find copper in the limestone close to the stock, with lead dispersed into cooler portions of the bed. The geological evidence suggests that both metals are carried in the same "solution."

The Schürman Series of elements, based on the position of the elements in the electromotive force series, has been used to explain mineral zoning; but again it gives no explanation of the role of heat and temperature, whereas all geologists know that, without certain minimum temperatures, no epigenetic ore deposition takes place—elements have no mobility.

In attempting to find answers to these sorts of problems, the writer tabulated various properties of the elements and their compounds in relation to heat and temperature and tried to find some correlation with the known facts concerning the distribution of metals in ore deposits.

It was found that the melting points of metals, when combined with the bonding characteristics of those metals, appeared to show a close relationship to the temperature conditions under which, geologists have found, these elements are mobile in nature. This is thus an empirical relationship, and various

[1] Numbers in parenthesis refer to References at end of paper.

theoretical deductions could possibly be made from it. It has led the author to the tentative conclusion however, that the concept of "hydrothermal solutions" may be quite invalid—a conclusion which has been reached by others, notably J. S. Brown (2), and that diffusion concepts, in which atoms or molecules acquire activation energies at certain critical temperatures, would better fit the observed data.

If this point of view is taken, it is possible to look at ore deposits from a new angle, and some interesting re-interpretations of known facts can be made. However, apart from these deductions, it is believed that the melting point relationship is itself an interesting fact which would bear examination and interpretation by others.

MELTING POINTS AND METAL ASSOCIATIONS

Bond Type

In Table I and Figure 1, elements have been arranged in order of their melting points, but they have also been divided into the two broad groups of Rankama and Sahama (17), the oxyphile and sulfophile elements. This grouping appears to have considerable significance in ore deposition and seems justified in this context because melting is dependent on bond energy, and metallic melting point means, broadly, the temperature at which the constituent atoms of a metallic crystal acquire sufficient thermal vibrational energy to overcome the cohesive or bonding energy which formerly held them together. But the oxyphile elements tend to occur in crystals in which ionic bonding predominates, while the sulfophile elements are those which occur in nature as native metals, sulfides, selenides, telurides, arsenides, etc., in which metallic or covalent bonding predominates.

Metallic melting point would be expected to have most significance (if any) for the sulfophile group, and this is what is found to be the case.

Melting Points of Sulfophile Elements and Temperature Zonings

The melting points of these elements appear to be indices of the minimum temperatures at which they are mobile in nature.

In substantiation of this statement, the reader is referred to the third column in Figure 1, in which the melting points of the sulphophile elements are shown graphically. It may be worth referring briefly to the various groups within which the elements fall.

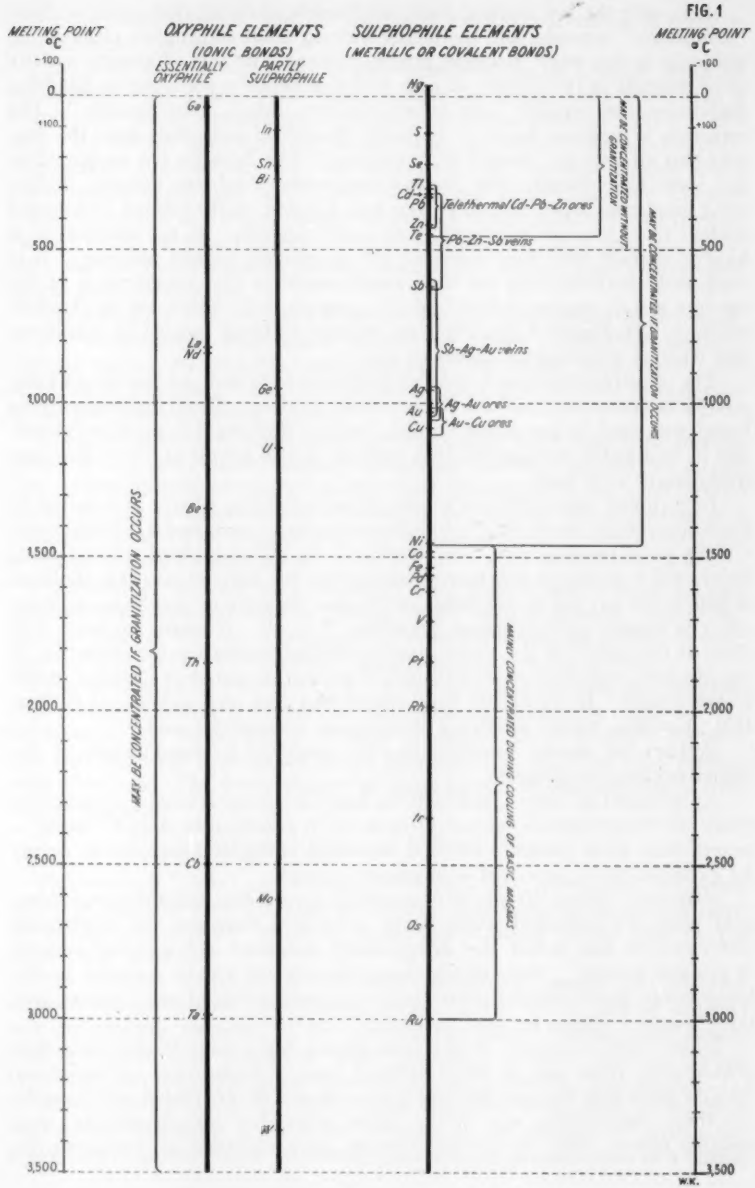
Thallium, Cadmium, Lead and Zinc.—Of all the elements in the earth's crust, these have similar melting points. As shown in Table I they follow each other consecutively. This is quite striking because, as far as is known to the writer, there is no explanation on "hydrothermal" theories of the association of lead and zinc in ore deposits, although this is one of the most striking of all metal associations. It is equally interesting that these elements have low melting points, because it is well known that lead and zinc may occur under geological conditions which indicate that high temperatures have not prevailed at the time of ore deposition. Thus, Newhouse has shown that sphalerite from the Tri-State deposits was probably formed at 115–135° C.

TABLE I

RELATIONSHIP BETWEEN MELTING POINTS OF ELEMENTS AND THEIR DISTRIBUTION IN GRANITES AND ORES

Elements	Melting point °C (10)	Common ore elements		Common rock-forming elements	
		Oxyphile	Sulphophile	Granitic	Gabbroic
Hg	−38.5		Hg	(Melting point of Hg does not indicate temperature of dissociation of sulphide)	
Cs	28.5				
Ga	29.75	Ga			
Rb	38.5				
P	44.1				
K	62.5			K	
Na	97.5			Na	
S	112.8		S		
In	115	In			
Li	186			Li	
Se	220		Se		
Sn	231.9	Sn			
Bi	271	Bi			
Tl	303.5		Tl		
Cd	320.9		Cd		
Pb	327		Pb		
Zn	419.5		Zn		
Te	452		Te		
Sb	630.5		Sb		
Ce	640				
Mg	651				Mg
Al	659.7			Al	
Sr	800				
Ca	810				Ca
As	814 (36 atm)		As		
La	826				
Ba	850				
Ge	958.5	Ge			
Ag	960.5		Ag		
Au	1063		Au		
Cu	1083		Cu		
U	1150	U			
Mn	1260				
Be	1350	Be			
Si	1420			Si	
Ni	1455		Ni		
Co	1480		Co		
Fe	1535		Fe		
Pd	1553		Pd		
Cr	1615		Cr		
Hf	1700				
V	1710		V		V
Pt	1773		Pt		
Ti	1800	Ti			Ti
Th	1845	Th			
Rh	1985		Rh		
Ir	2350		Ir		
Cb	2500	Cb			
Mo	2620	Mo			
Os	2700		Os		
Ta	2996	Ta			
Ru	3000		Ru		
W	3370	W			

FIG. 1


MELTING POINT °C
OXYPHILE ELEMENTS (IONIC BONDS)
ESSENTIALLY OXYPHILE
PARTLY SULPHOPHILE
SULPHOPHILE ELEMENTS (METALLIC OR COVALENT BONDS)
MELTING POINT °C
-100
0
+100
500
1,000
1,500
2,000
2,500
3,000
3,500
Ga
In
Sn
Bi
La
Nd
Ge
U
Be
Th
Cb
Mo
Ta
W
Mg
S
Se
Tl
Cd
Pb
Zn
Te
Sb
Ag
Au
Cu
Ni
Co
Fe
Pd
Cr
V
Pt
Rh
Ir
Os
Ru
Telethermal Cd-Pb-Zn ores
Pb-Zn-Sb veins
Sb-Ag-Au veins
Ag-Au ores
Au-Cu ores
MAY BE CONCENTRATED IF GRANITIZATION OCCURS
MAY BE CONCENTRATED WITHOUT GRANITIZATION
MAY BE CONCENTRATED IF GRANITIZATION OCCURS
MAINLY CONCENTRATED DURING COOLING OF BASIC MAGMAS
W.K.

It is only the low melting point sulphophile elements that occur in these "telethermal" deposits, and the higher melting point sulphophile elements do not occur in this way. Because, generally, there is no sign of granitic activity or of magmas in the vicinity of such lead-zinc deposits occurring in flat-lying limestones, the deposits have sometimes been called "telemagmatic." The reference to magmas, however, is purely theoretical and arises from the concept that all ores are derived from magmas. The facts do not support this, and some have thought that the low-temperature lead-zinc deposits in flat-lying limestones were deposited from cool solutions that obtained their metal content from previously formed "magmatic" deposits. If so, however, it is hard to explain why these solutions are so selective to lead and zinc. It is suggested, therefore, that the main requirement for the concentration of the ore is a certain degree of heat and this appears to be borne out by the field evidence. In Figure 1 these ores are labelled as being capable of concentration whether granitization occurs or not.

The elements occurring in smaller quantities with lead and zinc are of some interest in connection with the present point of view. Thus, thallium may be found with lead in the galena crystal, because thallium has a similar atomic size to lead and it is suggested that thallium is also mobile at about the same temperature as is lead.

In a similar way cadmium occurs in the sphalerite lattice; it is found in low-temperature ores as well as in high-temperature types and it is in the same melting point range as zinc. In contrast is the higher melting point element silver, which is able to substitute in galena for the same reason that thallium is able to do so; but in low-temperature lead deposits of the Missouri type, silver is present only in minor quantities, if at all. It seems probable that silver is not mobile at the temperature prevailing during the concentration of the Missouri type deposit even though, if present, it would be included in the galena crystal. In the higher temperature lead ores such as those at Broken Hill, Australia, higher quantities of silver are commonly found.

Perhaps for similar reasons iron-rich sphalerite is characteristic of the higher temperature deposits.

As indicated in Table I, although the lead-zinc group is mobile at comparatively low temperatures—temperatures at which granitization does not occur—nevertheless these elements will also be mobile if higher temperatures occur, for example, those associated with granitic activity.

Antimony, Silver, Gold.—It is generally agreed that the antimony-silver-gold veins are deposited under hotter conditions than are the telethermal lead-zinc ores, and, in fact, they are generally associated with a certain amount of granitic activity. Nevertheless these deposits are usually included in the lower temperature sections of temperature classifications of ore deposits, and there is good evidence for this.

Silver, Gold, Copper.—It has been known for a considerable time that gold-bearing veins rich in silver indicate lower temperatures of deposition than do those gold deposits that are low in silver. N. H. Fisher (4) brought out these relationships very well. Silver veins that contain stibnite, and, possibly galena, have, by general consent, been classified as comparatively

low-temperature deposits, and the possibility for this association to occur is well shown in Figure 1.

The ratio of gold to copper is also considered to be a minor index of temperature. At Cobar, New South Wales, the writer (19) found that a temperature zoning extends from the northern to the southern section of the field. At the northern end, the Great Cobar deposit contains chalcopyrite, magnetite and pyrrhotite. The ore contains about 3 percent copper and 1 pennyweight of gold per ton. South of this, the New Cobar and Chesney deposits contain 2 to 4 percent copper and 3 to 4 pennyweights of gold per ton. Farther south, the New Occidental deposit contains essentially gold and pyrite only, and the Peaks deposits, farther south again, contain mainly silver-gold ores as well as some lead.

The anticlinal fold with which the ore is associated pitches to the south, so that in composite longitudinal section, the higher temperature northern deposits appear to underlie stratigraphically the lower temperature ores occurring to the south. Regional studies suggest that the field is underlain by more or less concordant granite.

Gold and silver are linked in nature for reasons other than their melting points, as they have similar chemical properties, and have comparable atomic size. These factors, of course, govern their occurrence in the same crystal lattice, but the ratios of the two elements in ore deposits are dependent to a considerable extent on temperature, and this dependence on temperature can be linked to their melting points.

Sulphophile Elements with Melting Points Higher than Copper.—These elements are commonly said to belong to the early magmatic sulfides because, in general, they are concentrated in connection with the cooling of basic igneous rocks and are not commonly associated with granitic activity.

The melting point evidence (Fig. 1) indicates that possibly the temperatures attained during granitization may not be sufficiently high for the mobilization and concentration of these elements. There is ample evidence also that the basic igneous rocks are naturally rich in these high melting point elements. The concentration of these metals is discussed more fully later in this paper.

Oxyphile Ores and Melting Point

Reference to Table I and Figure 1 will show that, irrespective of melting point, the oxyphile elements, characterized by ionic bonding, are concentrated during granitic activity, which is in marked contrast to the case of the sulphophile elements.

The oxyphile elements are commonly enriched in granite and affiliated rocks as compared with basic igneous rocks. From this it may be deduced that the oxyphile elements, in the partition that occurs during granitization, tend to migrate towards granite rather than away from it; however, owing to the fact that the oxyphile ore elements are not essentially petrogenic (23), as granitization proceeds through a mass of sediments or other rocks, they tend to be segregated towards the margins of the granites or within the pegmatites; i.e., they do not commonly remain in the granitic mass as a whole,

although some dissemination of this type does occur, and has been well established in the case of uranium. It may at least be said that these elements have only a small tendency to move away from granite. This tendency is independent of metallic melting point, and appears to be one of the important factors governing the association of these metals in ore deposits.

It is possible that these elements migrate in combination with others, e.g., in the case of tin as SnF.

As suggested in Figure 1, the oxyphile or sulphophile character of an element is not absolute, and it is thought desirable to divide the oxyphile elements into two groups:

(i) Those which are most strongly oxyphile and occur mainly in the pegmatites. These comprise the elements tantalum, niobium, thorium, beryllium, and possibly the lesser known elements neodymium, lanthanium and gallium.

(ii) The more metallogenic or sulphophile elements indium, tin, bismuth, uranium, molybdenum, and tungsten. It may be noted that bismuth, tin and molybdenum form sulphides, but their general behavior in ore deposits seems to justify inclusion in the oxyphile group.

Some important oxyphile metal associations are discussed below.

Indium, Tin, Bismuth.—Although low melting point elements such as indium, tin and bismuth may occur together with very high melting point elements such as tungsten, it does appear as though elemental melting point may have some limited significance even in the association of oxyphile elements. Thus, tin, bismuth and indium are commonly found together, and these linked by melting point as shown in Figure 1. Indium is also found associated with the low-temperature sphalerites.

Uranium.—Uranium is markedly enriched in granite, and scintillometer investigations in several parts of the world have shown that radioactive granites are a very useful guide to uranium ore. Further, it has been pointed out by Gross (9) that the occurrence of uranium in certain sections of a granitic mass is a guide to the occurrence of other metals. It has generally been assumed that uranium, like all other metals, has been derived from the granites, and moves away from granite during cooling. May it not be true, however, that in accordance with its granitophile character, uranium, if it is present in surrounding sediments, and if temperature conditions for its activation are suitable, may actually move towards and be absorbed into granite rather than move out of granite? At least, it is suggested, its tendency to move away from granite is comparatively small.

The characteristic association copper-uranium-nickel-cobalt has always been puzzling because uranium is characteristic of granitic rocks, whereas the other elements are characteristic of basic igneous rocks. Some have thought that this meant that uranium also was in some way associated with basic rocks. However, it is seen that the melting point of uranium (1150° C) is the next highest after that of copper (1083° C), and this may help to explain this association. It is commonly found that, where oxyphile elements occur with sulfophile elements in ore deposits, the melting point relationship

exists. Thus, in the Kipushi Mine of the Belgian Congo the bornite-like mineral renierite, which has been described by Vaes (22), contains about 6 percent germanium. This deposit is also rich in copper, zinc and silver. The melting point relationship between germanium, silver and copper is seen in Table I. The association of the low-melting point indium with low-temperature zinc deposits has already been mentioned.

Although uranium concentration is normally associated with granitic activity, epigenetic deposits are also found in rocks that have not been so affected. Thus, at Lake Athabaska, Canada (11) the principal deposits are found in the old highly folded and granitized Tazin rocks, but some ore also occurs in the Athabaska Series, which unconformably overlies the Tazin, is much less folded, and is not affected by granitic activity. Thinking along "magmatic" lines made it difficult to explain the genesis of these deposits. The granite would normally be regarded as the source rock, but it is older than the Athabaska. Yet there is a relationship between the distribution of much of the ore, and the distribution of the granite-gneiss. On the other hand, it is hard to find a magmatic source for the ore in the Athabaska Series.

If it is thought that the essential requirement for the concentration of metals is heat, not magma, then it can be thought that the main concentration of uranium was associated with the granitization of the Tazin, but that sufficient heat was generated during the post-Athabaskan orogeny to reactivate some of the uranium.

Similar relationships have been discovered by B. P. Walpole (personal communication) in the Rum Jungle Province of Australia and the concentration of the deposit at Shinkalobwe was apparently not accompanied by granitic activity.

Molybdenum, Tungsten.—Molybdenum mostly occurs as the sulphide, but has oxyphile characteristics which are shown by its selective enrichment in granite, and by the metal association of the deposits in which it occurs. Thus, it may occur in veins in granite along with uranium, but may also occur with copper as in the porphyry copper deposits. In deposits such as those of Climax, Colorado, and in the pipes of New South Wales, tungsten is associated with the molybdenum. This type of deposit occurs in highly silicified phases of granite, in contrast to those of copper and nickel which are concentrated in the more basic igneous rocks.

Pegmatitic Elements.—The elements tantalum, niobium, thorium, and beryllium are virtually exclusive to pegmatites, which may also contain uranium and, more rarely, tin. Less commonly, the low melting point element bismuth may also be present, either as a sulfide or in the metallic form. These associations illustrate the importance of the oxyphile classification in the respect that the elements belonging to this group have little tendency to move away from granite or to positions of low temperature. They are akin to the petrogenic or rock-forming elements.

Diagnostic Value of Metal Associations

The melting point relationship to metal associations may be used in assessing the origin of various metalliferous provinces. Thus, cobalt and

copper are two of the commonest associates of uranium, but they are believed to have different meanings in different geological contexts. Thus, in the cooling of a basic igneous magma some concentration of cobalt commonly occurs. This is the case with the deposits of Cobalt, Ontario, and for those in the Cloncurry District of Queensland, Australia (18). Copper may be, and commonly is, associated with such cobalt deposits, but in general where these elements occur under such conditions they are no guide to the occurrence of uranium because basic igneous rocks are commonly low in uranium content. Extensive testing in the Cloncurry district has not revealed the presence of uranium associated with such ores.

On the other hand, uranium, copper, cobalt and vanadium have a somewhat similar geochemistry in the exogenic cycle and they are deposited under rather similar conditions during sedimentation. If source sediments rich in copper and uranium are subjected to sufficient temperatures to make these elements mobile, they tend to occur together because of their similarity in melting points which indicates that they will move within about the same temperature range. Vanadium is, in general, not concentrated during heating, and cobalt concentration, even during granitization, is slight.

The copper-cobalt-uranium association of the Rhodesia-Katanga belt could be regarded as essentially a syngenetic one because, in general, cobalt would not be expected to be mobile at the temperatures prevailing in these areas during ore deposition.

Similar reasoning could be applied to the Colorado Plateau uranium-vanadium deposits and these will be discussed in greater detail at a later stage in the present paper.

Suggested Theory

In the preceding pages an attempt has been made to utilize only the observed facts of geology and the equally factual melting point data. In the following discussion, however, an attempt is made to provide some theoretical basis and to suggest a mechanism whereby the elements found in ore deposits become mobile. This will be done briefly because there still appear to be many unknown features and the writer does not feel at all certain that he is able to suggest the correct explanation.

It has already been pointed out that metallic melting point appears to have most geological significance for those elements in which metallic or covalent bonding occurs.

It is suggested that, for the elements which readily form sulphides, the melting point of the element is, in general, an index of the temperature of dissociation of the sulphide. Under this concept, the minimum temperature at which movement may occur is that at which appreciable dissociation exists, thus allowing movement in the atomic state to take place.

Barnes (1) has described in a clear manner the diffusion of copper into nickel. The experiments he describes were facilitated by the use of radioactive isotopes. At temperatures within "a few hundred degrees of melting point" the diffusion of the atoms becomes most marked. Rate of diffusion

is an exponential function of absolute temperature. Atoms diffuse most easily along grain boundaries and other lines of weakness, and, as is well known, it is along such lines of weakness that elements move in geological processes. Some of the photographs published by Barnes, which show the results of diffusion, resemble quite closely microphotographs of ores.

Many writers, especially, perhaps, Lapadu-Hargues and Perrin and Roubault in France, and Ramberg at Chicago, have suggested that various types of diffusion are important in geology, and the present findings may bear this out. If the atoms moved to cooler positions in which they could no longer exist out of combination with other elements, and were thus fixed (as sulfides for example), the result would be to produce a concentration gradient with a consequent movement of the metallic element towards the point at which it was fixed and withdrawn from the system.

It is difficult to relate melting point to the solubility of metals and their compounds and, in the writer's opinion, the whole concept of "hydrothermal solutions" needs re-examination. Observations have proved, of course, that small quantities of metals are present in hot spring waters, but it is doubted, by the writer, that the phenomena associated with granitic activity, among which is the deposition of a high proportion of ore deposits, can legitimately be compared with hot spring activity.

The writer is unable, at this stage, to postulate a definite diffusion mechanism which fits all cases. In the case of diffusion at low temperature such as appears to him likely for the telethermal lead-zinc deposits, the function of temperature could be to free the lead and zinc ions from crystal lattices, thus enabling them to enter liquid present along crystal interfaces or in pore spaces, through which they could diffuse. Garrels and Dreyer (7) have found that diffusion in liquids may be very important in this type of ore deposition. It cannot be forgotten, however, that the melting point appears to be an index, not only of the temperature at which elements begin to move, but also of that at which they cease to move. Diffusion in liquids does not seem to fit this relationship.

It is not thought, however, that ore deposition results simply from thermal diffusion, as other factors are involved. Thus, in a significent paper, Fyfe (5) has built upon the work of Goldschmidt (8) and has shown the importance to geology of the relationship established by Pauling between the electronegativity of an atom and the type of bond formed by it. Thus, the strongly electropositive elements tend to form ionic bonds; these are the oxyphile elements, which are selectively concentrated in granites. The combination of strongly electropositive cations and electronegative anions forms stable compounds that are characteristic of granite. This has been discussed by Ramberg (14, 15) who has made important contributions to this type of thinking.

During sedimentation, elements are distributed largely without respect to their position in the electromotive force series, and it is suggested that, if, later, sufficient temperatures are attained for the activation of these elements, they will tend to re-distribute themselves so that compounds that are stable at high temperatures may be formed. The system moves towards a condition

of minimum potential energy and maximum bonding energy. The sediments, largely composed of loosely bonded minerals, have a high potential to change to the high lattice energy granite. Basic igneous rocks are more stable than most sediments in this respect. This is thought to be part of the directionalism of granitization referred to by the present writer in a previous communication (20).

This directionalism commonly has important local significance in ore deposition. Thus, just as during the first cooling of the earth's crust certain chalcophile elements such as copper, nickel and cobalt became selectively enriched in the more basic igneous rocks and the lithophile elements were concentrated in granite, similarly, if these elements are mobilized in the vicinity of a contact between granite and a basic rock, the chalcophile elements will tend to move towards the basic rock and the lithophile elements will move towards the acid pole. Evidence for these remarks will be given below in the discussion of some representative ore deposits.

The problem of the diffusion of elements in nature would be greatly simplified if it could be assumed that, during periods of heating and orogenic and magmatic activity, differences of electrical potential existed in the earth's crust. As is known from experimental evidence, such differences would speed up diffusion and would help to explain the directionalism mentioned above. The function of temperature would then be that of activating the elements, and they would diffuse under the influence of an electrical field. Under this type of thinking, granitization and ore deposition are viewed as the neutralization of an electrochemical disequilibrium set up during sedimentation and volcanic activity (20).

However, the evidence of ore deposition indicates that metallic elements commonly migrate to positions of relatively low pressure, and it seems likely, as indicated by Ramberg (15), that pressure gradients have an important influence in the migration of elements.

MELTING POINT AND FACTORS OF CONCENTRATION OF METALS

In writings on ore deposits it is not generally emphasized that some elements have been concentrated in nature to a remarkable degree whereas others are much more dispersed. Still less have reasons for these differences been greatly remarked upon.

In Table 2 some data have been assembled in order to bring out these points. In the fifth column are shown "factors of concentration" for various elements. These are the percentages of the metal generally found in ore deposits, compared to the percentages generally found in igneous rocks. These factors are regarded as being only broadly characteristic, but they indicate the contrast that exists between the high degree of concentration of elements like lead and antimony as compared to the natural concentration of nickel, cobalt and chromium, for example.

In the last column of Table II an "index of concentration" has been obtained by dividing world production by abundance in the crust multiplied by price. The price factor has been included as it is obviously a stimulus to production.

TABLE II

COMPARISON BETWEEN ABUNDANCE OF ELEMENTS AND THEIR CONCENTRATION IN ORE DEPOSITS

		Metal	Abundance in igneous rocks, g/ton[1]	Abundance in granite, g/ton[1]	Abundance in gabbro, g/ton[1]	Factor of concentration in ore compared to igneous rocks	Approximate world production 1948, tons	Approx. price, U. S. cents per lb.	Index of concentration: Production / (Abundance × Price)
Concentrated during granitization	Sulphophile elements	Cd	0.15	?	?	?	4,800	180	2,500
		Pb	16	20	5	10,000	1,300,000	17	50,000
		Zn	132	200	100	1,000	1,700,000	12	15,000
		Sb	1	0.3	?	100,000	41,000	35	15,000
		Ag	0.1	?	?	1,000	6,850	1,080	
		Au	0.005	0.005	0.1[2]	1,000	1,250	42,000	
		Cu	70	15	150	5,000	2,341,000	22	10,000
Concentrated during cooling of basic igneous rocks		Ni	80	8	100	100	150,000	35	500
		Co	23	5	100	150	6,200	165	20
		Fe	50,000	2,500	100,000	100	210,000,000	0.5	
		Cr	200	5	500	100	1,000,000	100	500
		V	150	10–30	100–300	Low	1,800	125	1
Concentrated during granitization	Oxyphile elements	Sn	40	50	8	1,000	150,000	120	300
		U	4	4?	11	10,000	10,000	800	20?
		Bi	0.2	2	?	100,000	1,400	200	200
		Mo	2.5–15	12	3	1,000	14,000	75	200
		W	8?	10?	4?	1,000	32,000	150	200
		Th	1–5	13	5		?	400?	
		Cb	24	30	7		1,500	270	5
		Ta	2.1	4	1		200	250	5

[1] Mostly from the compilation of Rankama and Sahama (17). Metal contents of igneous or sedimentary rocks are not uniform. Differences help to give rise to metalliferous provinces.

[2] Some "greenstones" in the Western Australian gold province.

By comparing Table II with Figure 1 it is believed that some constructive results may be obtained. Low melting point elements that are mobilized at low temperatures, for example cadmium, lead and zinc, have very high indices of concentration. On the present theory, these elements may be mobilized at temperatures at which other elements remain dispersed and such a result would thus be expected.

It is during granitic activity that the most extensive re-distribution of materials takes place, and those elements that may be activated at the temperatures prevailing during such activity have comparatively high indices of concentration. The cooling of basic igneous rocks is in marked contrast to the above, and those elements (Fig. 1) that are associated with this process have low indices of concentration. Thus, during the crystallization of a hypabyssal or plutonic basic igneous rock, containing nickel and cobalt, these elements have only a limited tendency to diffuse out of the basic magma which is their natural habitat.

Much more important concentrations of nickel and copper, for example, may be found if such basic rocks, after consolidation, are intruded or replaced by granite or by other igneous bodies of a composition different from that of the intruded basic rock. Under such conditions, temperatures for diffusion exist and concentration gradients are set up; the chalcophile elements are fixed in the most basic rock in the neighborhood in which conditions for diffusion exist.

As previously pointed out, the concentration of metals does not depend entirely on activation temperature, as it is a function also of the petrogenic or metallogenic characteristics of the particular elements. Thus, the pegmatitic elements thorium, niobium and tantalum have low indices of concentration because of their rock forming characteristics. They are oxyphile elements. The element vanadium has an extremely low index of concentration and, in fact, is rarely found in epigenetic ore deposits. It has a high melting point and may possibly be activated only at very high temperatures. Additionally, however, it combines with other elements to form micas.

GENESIS OF SOME DEPOSITS IN TERMS OF ABOVE PRINCIPLES

In the following pages the genesis of some metalliferous provinces is discussed briefly in order to illustrate some applications of the points of view outlined above.

Colorado Plateau Uranium-Vanadium Field

Much has been written concerning the origin of these deposits, and most writers have thought that they are essentially syngenetic ores. Others, however, have considered that they are "hydrothermal." The writer considers that a primary concentration of major intensity has occurred during the sedimentary cycle, though evidence clearly shows that some reconcentration has occurred. The author has no intention of recapitulating the published arguments, but would like to discuss the widespread presence of vanadium in the light of the data shown on Tables I and II, in Figure 1.

It was previously remarked that, during granitization (or "granitic intrusion"), granitophobe ore elements with melting points higher than about 1100° C are not commonly concentrated. Vanadium has a melting point of 1710° C, so that the temperature at which it is mobile in the primary zone may be high. It has been noted that, although vanadium is relatively abundant in the crust (basic igneous rocks contain 100 to 300 g/ton), its concentration into ore deposits is quite rare (Table II). It is essentially a petrogenic element.

Now, there is no sign in the comparatively stable Colorado region that extensive granitic activity has taken place, and such activity could not be expected in such a tectonic environment. There is no evidence that temperatures which could lead to the migration of vanadium have affected these rocks. The presence of asphalt, the widespread occurrence of gypsum, and the fact that salt domes, with some oil, underlie, in places, the uranium-bearing Mesozoic sediments, constitute proof that no such temperatures have been reached.

On the other hand, it is well known that vanadium and uranium are deposited from surface waters under reducing conditions, and that vanadium is commonly associated with hydrocarbons. Epicontinental beds deposited in comparatively shallow, discontinuous, basins are associated with syngenetic ore in many parts of the world. The presence in the Palaeozoic and Mesozoic rocks of evaporite deposits, such as salt and gypsum, points to close basin conditions.

The reconcentration which has occurred must have been effected by solution in meteoric waters; the melting point evidence indicates that it is most unlikely that the vanadium has been concentrated by thermal processes.

Rhodesia-Katanga Copper-Cobalt-Uranium Belt

Oosterbosch and Schuiling (13), in an important paper, reviewed impartially the evidence for the origin of the Katanga ores, and considered that an epigenetic origin appeared the more probable. Again, the writer does not wish to recapitulate the published evidence, but to discuss especially the occurrence of cobalt in this region.

The Katanga-Rhodesia belt produces about 75 percent of the annual world production of approximately 6,200 tons of cobalt, but this is only partly expressive of the enormous cobalt anomaly (from a geochemical point of view) that characterizes this metalliferous province as a whole.

Now there can be little doubt that vein-like deposits, such as Shinkolobwe, with the association copper-uranium-nickel-cobalt are of thermal origin, or have been concentrated in a hot environment. These elements group together in Table I and Figure 1. The massive accumulations of uraninite in fault structures also indicate this. It may further be noted that the zinc-germanium-silver-copper ore Kipushi, which occurs in the Kakontwe limestone, and is associated with faulting, has been concentrated by epigenetic processes.

However, these deposits are not typical of the Rhodesia-Katanga belt, where copper and cobalt minerals mainly occur disseminated in beds. The

ores of Rhodesia occur mostly in arkoses and shales, whereas those of Katanga are in dolomitic shales and dolomites, though the beds are of much the same age. As shown in Table I, the melting point of cobalt is very high (1480° C). It belongs to the series of elements that are not normally concentrated to any great extent in connection with granitic activity, although minor deposits occurring at granitic contacts are known; it belongs to the so-called "early magmatic sulphides" concentrated during the cooling of basic igneous rocks—as in Cobalt, Ontario and in the Cloncurry District of Western Queensland (18). As shown in Table II, it has an index of concentration of about 20, as compared with 50,000 for lead. The production from undoubted epigenetic deposits is small indeed compared with the abundance of the element in the crust.

Now the bedded ores of Katanga are not closely associated either with granite or with basic igneous rocks, and the sediments themselves, although they have been thrust and folded, have undergone little metamorphism. The dolomitic shales are still shales, with very well preserved bedding, and lime and magnesian carbonates have not been converted to pyroxenes or amphiboles. This is definitely not the temperature environment for the occurrence of epigenetic cobalt. It may be significant, also, that vanadium occurs in this province, and the discussion of the Colorado ores applies here.

The author claims no originality in suggesting that the Rhodesia-Katanga metalliferous province owes its existence primarily to the syngenetic accumulation of metals in shallow basins. Garlick and Brummer (6) consider that they have shown that the granites of Rhodesia, which were thought to have been responsible for the occurrence of the ore, are, in reality, pre-ore in age. The syngenetic character of the ore is suggested by the low pyrite content, by the dominance of chalcocite even at great depths, by the lack of introduced gangue minerals, by lack of relationship between ore and structure, by the great size of the deposits, and by the strict localization of the ore in sediments which, though of varying type, are of much the same age.

Ores of the Rand-Rhodesia-Katanga type may have undergone some rearrangement, probably, in the author's opinion, by the effects of limited heat; but these effects seem correspondingly limited. Provinces in which the accumulation of metals is due primarily to non-thermal processes have quite a different geological aspect from those in which thermal processes have been dominant, and the difference is of considerable economic significance.

Western Macdonnell Range Copper-Nickel Province, Australia

In this area in Central Australia, the writer (21), working in collaboration with A. D. M. Bell, has noted the existence of bedded copper-nickel ores in a group of sediments of Upper Proterozoic to Cambrian age. These sediments unconformably overlie the Middle Proterozoic (?) rocks, which are the youngest in the area to have been affected by extensive orogenic and magmatic activity. No granite or igneous rocks intrude the copper- and nickel-bearing sediments and they are only gently folded. The mineralization is associated with shoreline facies and with euxenic conditions of sedimentation.

The metals occur in arkoses and in siltstones. Dolomites and dolomitic shales of the Collenia type, reminiscent of Katanga, underlie the ore-bearing formation.

It is considered that at no stage in the history of these rocks has there been sufficient temperature for the extensive mobilization of copper and nickel to occur and true epigenetic copper and nickel deposits are not found in such a geological environment. The ores are regarded as being of syngenetic origin and these conditions are associated with syngenetic ores in many parts of the world.

Preliminary investigation indicates that, in the Macdonnell Ranges, as in Rhodesia-Katanga, the copper-nickel mineralization occurs in or about the same stratigraphic position throughout the region.

Lead Deposits, Missouri

Much has been written concerning the genesis of these deposits, and, as mentioned above, it has been difficult to account, in terms of solubility, or on theories of magmatic differentiation, for the occurrence of this type of ore. The ore of south-eastern Missouri is contained in the Bonne Terre limestone which is about 400 feet thick, and rests on the Lamotte sand, 50 to 100 feet thick. It has been established by geologists of the St. Joseph Lead Company (personal communication) that some major deposits occur over buried hills of Precambrian granite, above which the flat-lying sediments are slightly domed, and, in detail, the best shoots within the deposits occur in minor domal and anticlinal structures. No granitic activity has affected the beds, and there is no sign of any magmatic activity that could be held responsible for the accumulation of the ore.

In Table I and Figure 1, it is seen that the melting points of lead and zinc are quite low, and it is known that these metals move at temperatures well below those associated with granitic activity. Just as zinc and lead move out into the colder portions of a limestone bed near a granite contact, so, similarly, it is thought, during diagenesis, lead and zinc move away from the heavily loaded and warmer flanks of domes to the less heavily loaded crests. In a similar manner, under higher temperature conditions, as at Broken Hill, Australia, lead and zinc move towards the crests of folds. These phenomena are probably similar in type to those resulting in the formation of the quartz saddle reefs, except that lead and zinc may move at temperatures much below those associated with granitization, whereas silica migrates under higher temperature conditions.

In Tunisia, lead-zinc deposits are associated with diapiric structures in which sandstones pierce overlying dolomite. The lead-zinc ore occurs in the dolomite near the sandstone. This is very similar to the accumulation of oil near salt plugs. There is a close analogy between the occurrence of oil and the occurrence of lead-zinc deposits of the low-temperature type.

The mineralogy of this type of deposit has already been discussed.

Sudbury, Ontario

At the Creighton Mine, Sudbury, there are three main rock types which are, in decreasing order of age, the hanging wall norite, the footwall granite, and narrow bodies of diorite that are generally close to the contact, and with which the nickel-copper ore is closely associated.

The world-wide association between nickel and basic igneous rocks, and the fact that much of the Sudbury norite contains approximately 0.015 percent nickel, shows that the norite has an important genetic relationship to the ore, and it is partly for this reason that it was formerly thought that the nickel had settled out of the norite by gravitation. This theory tends to ignore the fact that the younger footwall granite commonly contains a good deal of the ore, and for this and other reasons some writers considered that the nickel deposits possibly had little to do with the norite and were of "hydrothermal" origin. The present author suggested in 1949 (20) that the granite was important for the concentration of the nickel which had been derived from the norite.

The Sudbury diorite may be regarded as a transition rock, resulting from the quenching of an assimilation of the norite by the granite. Numerous remnants of basic rock in the granite suggest that a considerable body of norite has been digested by the granite. The nickel and copper derived from this basic rock would migrate towards and into the most basic rock in which conditions suitable for the movement of metals occurred. This is the diorite. This type of phenomenon is considered to be simply a repetition of the partition of nickel and copper between granite and basic igneous rocks which has occurred in many ages of geological history; gabbros normally contain 10 to 15 times as much nickel and copper as do granites (Table II). Had the norite again become magmatic, the nickel would have become dispersed in this rock; the narrow bodies of diorite and the thin layer of hot norite near the contact were ideal for trapping the nickel and copper.

As pointed out above (Fig. 1) nickel can move only at high temperatures and will not migrate into cool regions. The high temperature required for the movement of nickel is expressed in the fact that the ore at Sudbury is found mostly at the contact, although disseminated nickel is found in shears that occur in the norite at no great distance from the contact.

As is the case with many contacts of this type, there has been movement along the junction, and this has governed to a considerable extent the final localization of the ore. Nevertheless, in several mines there is a close association between the diorite and the orebodies, and, in some cases, diorite with a large content of sulphides actually constitutes the ore. Relationships possibly similar to those described above are seen in a number of porphyry copper deposits of the South Western United States.

Ray, Arizona

At Ray, which has been described by Clarke (3), a sill of diabase intrudes the siliceous Pinal schist, and both of these rocks are cut by younger monzonite.

A large proportion of the payable primary ore occurs in the diabase. Although it is thought, by the writer, that the widespread diabasic intrusives occurring in conjunction with many of the porphyry copper deposits of Arizona have been the ultimate source of much of the copper found there (in the same way that the Sudbury norite is believed to be the source of the nickel at Sudbury) it is very likely that the diabase at Ray did not have its present content of about 1 percent copper when it was intruded, but that it has absorbed much of this copper during subsequent granitic activity. Near the Ray deposit there are diorites containing 0.1 to 0.2 percent copper, a copper content that is quite anomalous for primary rocks of this type. The adjoining granite porphyry contains only traces of copper. It is considered that diorites and monzonites of these types may be regarded as bodies of rock resulting from the quenching, owing to a fall in temperature, of elemental interchange, before the normal equilibrium product, granite, had been formed. These monzonites and diorites may be equivalent to the diorite of Sudbury, and perhaps should not be regarded as a "source" of the metals, as they have been in the past.

Under these concepts the "holy" monzonite becomes a favourable host rock when adjacent to more acid rocks. If diorites or diabases exist and they are sufficiently hot to allow diffusion to occur within them, they are more "holy" than the monzonite.

CONCLUSION

The writer previously pointed out (26) the world-wide association between types of sedimentary and volcanic rock provinces and types of metalliferous provinces, and this seemed to him to throw doubt on the magmatic differentiation theory of ore genesis. It could have been possible however, that, during periods of heating and orogeny, solutions were generated within the sedimentary and volcanic piles that were capable of dissolving and concentrating the formerly dispersed metallic elements. Certainly water is associated in some way with many types of ore deposition.

However, the melting point relationship suggests different possibilities, and it is submitted that these should be considered along with other hypotheses.

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It is emphasized that the views expressed in this paper on the possible importance of melting point are entirely those of the author.

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THE ORIGIN OF THE ROAN ANTELOPE COPPER DEPOSIT OF NORTHERN RHODESIA[1]

G. R. DAVIS

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[1] This paper is condensed, with slight additions, from a dissertation presented in 1949 to the University of South Africa for the degree of Doctor of Philosophy, and is based on information available to the author between 1943 and 1947.

ABSTRACT

The evidence of structural conditions, mineralography and petrography is presented and then examined in relation to the rival theories of genesis of this bedded sulfide deposit. The absence of a possible post-Roan igneous source of mineralization, the relationships of sulfide zoning and the essential contemporaneity of the copper sulfides, the pre-folding age of the sulfides, the absence of introduced gangue minerals, the abrupt stratigraphic limitation to ore, and other features, all point away from an epigenetic origin for the mineralization. The field and microscopic features of the deposit are reasonably explained by the favored theory of biochemical sulfide syngenesis later modified by dynamothermal metamorphism acting under strong structural control.

INTRODUCTION

ALL ore deposits present genetic problems, some of detail, others of far-reaching significance to geologic science. Few indeed offer a more significant and absorbing problem in ore genesis than the great bedded copper sulfide deposits of the Northern Rhodesia Copperbelt.

It was early apparent that the mode of origin of these copper deposits was a controversial subject—they might be syngenetic or they might be epigenetic. The intensive prospecting and development of the Copperbelt after 1926 led to several publications in the early thirties. The opinions of genesis expressed in these papers are so much in favor of an epigenetic origin for the ores that one might suppose the controversy to be no longer existent. During the intervening years, however, much additional information has been gathered, and in the minds of local geologists it has led to the belief that the original controversy still exists.

GENERAL GEOLOGY

Location and Physiography.—The Roan Antelope deposit is situated at the southern end of the Copperbelt of Northern Rhodesia, in flat bush country. The Luanshya River and its tributaries, which drain the area into the Kafue River, run in shallow open valleys, with many small-scale meanders, and originate in open grassy spaces known as dambos. The area is in the first stages of peneplane dissection, and lies at about 4,200 feet above sea level, with the quite insignificant relief of 300 feet in five miles.

Gray's Geological Column.—The general regional geology was described by Gray after the mapping of the Nkana Concession under his direction in 1929 (1) [2] and 1930 (7). Gray's map is reproduced as Figure 1. The geological column given here expresses the latest revisions to Gray's original work, after Garlick and Brummer (13).

The Basement Schists, together with granite masses, form an eroded floor upon which the System of the Katanga was laid down. The oldest members of this System constitute the Mines Series, which consists of the Lower and Upper Roan Groups, overlain conformably by the Mwashia Group of felspathic sandstones and banded shales. All the bedded copper sulfide ores

[2] Numbers in parentheses refer to Bibliography at end of paper.

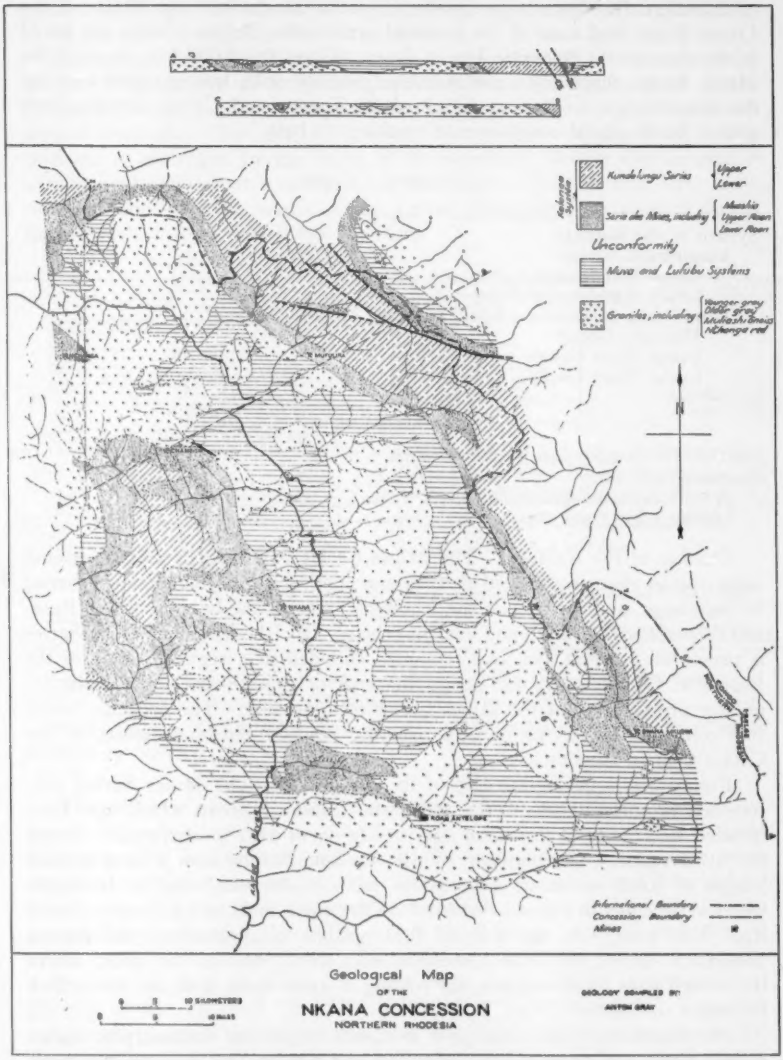


FIG. 1. Reprint of "Geologic Map of the Katanga-Rhodesia Copper Belt." By Anton Gray. With acknowledgments. ECON. GEOL., Vol. 25, p. 786.

of Northern Rhodesia occur in the felspathic sandstones and shales of the Lower Roan, and most of the oxidized ores of the Belgian Congo are found in the dominantly dolomitic Upper Roan. Upon the 5,000 feet or so of the Mines Series there rests conformably, possibly with transgressive overlap, the Kundelungu Series, consisting of the Lower and Upper Groups, each with a fluvio-glacial conglomerate marking its base.

Geological Column

Gabbro intrusive into Upper Roan Group
System of the Katanga
  Kundelungu Series
    Upper Kundelungu Group
    Lower Kundelungu Group
  Mine Series (also named Roan or Bwana Mkubwa Series)
    Mwashia Group
    Upper Roan Group
    Lower Roan Group

Great unconformity

Old Granite intrusive into Lufubu System
Basement Schists
  Muva schists and quartzites
  Lufubu schists and gneisses

Outline of the Geology.—The Mines Series has a north-westerly trend, occurring in elongated folded patches surrounded by the Kundelungu Series in the Congo, and resting, on the Rhodesian side of the border, on the Basement Complex of granite and ancient schists. In Rhodesia the Mines Series is preserved in great synclinal remnants enfolded in a regional dome of the Basement Complex; in the Congo the lack of granite and schist indicates greater preservation of the Mines Series from erosion. The orogenic forces that contorted the whole mineral province reached greater intensity in the Congo than in Rhodesia.

Figure 2 is a geological map of the Roan area. The Mines Series, surrounded by ancient rocks of the Muva and Lufubu Systems which have been invaded by granite of pre-Roan age, trends north-west to south-east. From the little-explored synclinorium of the Muliashi-Baluba area a long narrow tongue of Roan sediments extends six miles to the south-east as an asymmetrical syncline, in places overturned on the north limb, and generally deeper than it is wide. As the nose of this syncline is approached, the intense subsidiary folding of Roan Extension dies away, and at the nose, where the trough rises to the surface, the folding is more open, with the north limb no longer overturned (Figs. 2–6).

The Basement Schists comprise a variety of ancient metamorphic rocks, mainly biotite schists with dark granulites and gneisses, and banded quartzites showing ptygmatic folding. These rocks are more highly metamorphosed than the Roan sediments, and are made up of an impressive assemblage of metamorphic minerals. The biotite schists are well represented in the under-

ground workings, and may be easily cleaved along the planes of schistosity, which parallel the strike of the Mines Series.

The Mines Series, overlying the schists unconformably, is represented by its lower two groups at Roan Antelope and Roan Extension, parts of the Mwashia Group and Kundelungu Series being present only on the western part of Muliashi. The extent to which the members of the Roan Group crop out is controlled by the depth of the syncline. Where the syncline is narrow and shallow the members of the Upper Roan Group have been removed, and even the arkose of the Lower Roan Group is missing at the Roan Antelope-Roan Extension boundary.

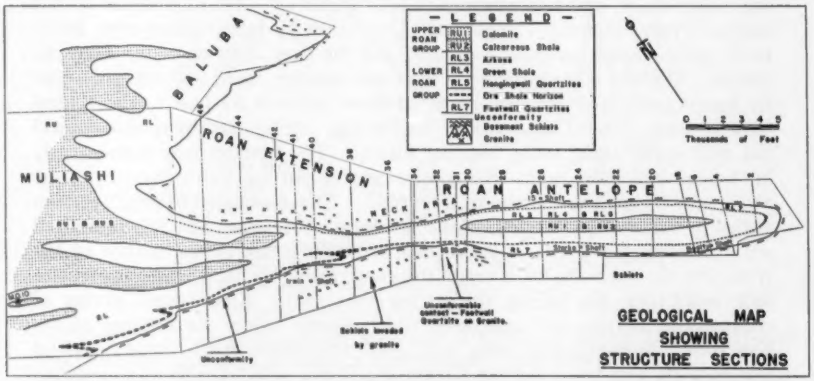


FIG. 2. The main features only are shown. The numbered lines locate structure sections, some of which are referred to in the text.

Note: In Figs. 3 to 5 inclusive, workings and drillholes are not shown in order to avoid confusion on this scale.

The members of the Lower Roan Group, which contains the ore horizon, are all feldspathic sediments. *The Footwall Quartzites* consist of a variable thickness (due to the irregularities in the basement on which they were deposited) of grits, sandstones, quartzites, conglomerates, and interbedded thin shales. The rocks are brownish or grayish on the whole, with a white recrystallized quartzite about 150 feet from the top. Lateral variation of many horizons is common, and thin conglomerates may persist over only a few hundred feet of strike. A thick basal conglomerate is present, and the top of the Footwall Quartzites is marked by a remarkably persistent conglomerate, generally only about four feet thick, which is known as the *Footwall Conglomerate,* since it marks the base of the mineralized beds above. Two other fairly persistent conglomerates lie between the two mentioned. False bedding is universal in the Footwall Quartzites, and disseminated magnetite is widespread.

The Footwall Schist lies immediately above the Footwall Conglomerate. This very persistent horizon is generally about two feet thick, although Sharpstone (2) reports an increased thickness of 20 feet at Muliashi. This highly micaceous schist is mostly thoroughly decomposed and it may carry secondary copper minerals. Where not decomposed, it is a minutely contorted quartzitic or calcareous mica schist. During folding, much stress was obviously relieved by movement within this weak bed, lying between the strong quartzites below and the compact "ore shales" above.

The "Ore Shale" Horizon averages about 60 feet in true thickness, and consists of dark gray banded hornfels and metamorphosed argillaceous rocks. Though known as "shale," the rock is typically too hard and and compact to merit this name, and is sometimes called "argillite." The upper part of the horizon grades into the Hangingwall Quartzites by intercalation with sandy beds, which rapidly become dominant, and the base rests upon the Footwall Schist. The ore shale horizon is relatively massive, hard and compact near its hangingwall, and becomes more schistose towards its base. The typical rock is finely bedded, but due to hornfelsing during metamorphism it will not split easily along many bedding planes. The horizon may conveniently be divided into three units—the copper-bearing portion and a barren portion above and below, as shown in Figure 7. The footwall "barren" portion varies in thickness according to the locality in the mine, and is mineralized with disseminated pyrite. Above this, with no break in the nature of the rock, lies the orebody, of average thickness about 25 feet. The ore shales look much like the barren shales, but they carry disseminated grains of chalcopyrite, bornite and chalcocite, which mostly follow the bedding of the host rock. Mineralization ends with great abruptness at the hangingwall of the orebody, and the overlying barren shales are entered with absolutely no change in the appearance of the rock. Contrasting with this sharply demarcated hangingwall, the footwall is an arbitrary horizon fixed by an economic cutoff value to the mineralization, which fades away downwards. The nature of the ore shale changes along the strike. Hard and compact in the east, it becomes more schistose and softer to the west due to more intense dynamic metamorphism. The ore shale horizon is persistent, maintaining the copper mineralization in the same stratigraphic position for miles, although variations in stratigraphy and mineralization occur on Muliashi. The average copper content of the orebody, also, is remarkably uniform, near 3.3 per cent total copper.

The Hangingwall Quartzites compose about 230 feet of hard feldspathic quartzites. The typical members are blue-gray and gray, fine-grained, impure quartzites, interbedded with gray shaly quartzites and white or pink feldspathic quartzites and arkoses. The latter are characteristically false-bedded, a feature generally marked by grains of magnetite. Conglomerates are absent. This formation is not to be confused with the generally more gritty Footwall Quartzites, although they have in common such features as the alternation of coarse and fine horizons, lateral variation, false-bedding, and a general tendency to carry disseminated magnetite grains. The formation grades upwards into:

The Green Shale Horizon, which is about 40 feet thick. Sharpstone (2) describes this as a poorly-bedded, light olive-green formation, in places schistose and micaceous. Dolomite may be developed at its base, as in the Storke Shaft area.

The Arkose horizon, the uppermost member of the Lower Roan Group, overlies the Green Shale rather abruptly. About 450 feet thick, this formation consists principally of coarse pink arkose and feldspathic quartzite, pebbly in places. Bedding is not well marked, but in some places fine false-bedding is to be seen.

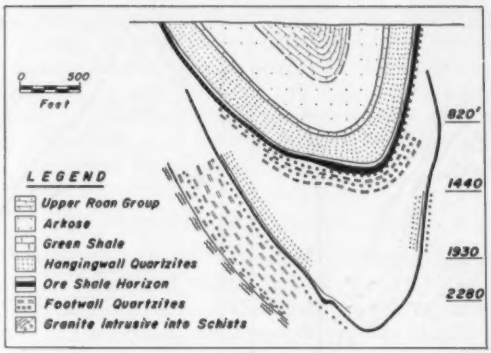


FIG. 3. Structure Section 18, with part of Structure Section 24 superimposed to illustrate the change in shape of the syncline. Note how, on S.S. 18, the footwall Barren Shales are absent above the Footwall Conglomerate at the trough and on the north limb (cf. Fig. 14). S.S. 24 is regarded as the type section.

The Upper Roan Group is composed of rocks of a different nature. The arkose grades upwards through interbedding into dark gray and green, arenaceous, highly Calcareous Shales. Overlying these is the Dolomitic Limestone, never completely present on the Roan, and in places eroded away altogether. It is described by Sharpstone (2) as an arenaceous or argillaceous dolomitic limestone, commonly serpentinized, recrystallized or silicified, and containing locally considerable pyrite.

Pre-Roan Group Features.—The basal members of the Roan Group were deposited upon the schist-granite complex, which had been eroded to an apparently mature landscape. Schist terrain was practically flat, whereas ridges and hills were preserved where the more resistant granite formed cupolas in the invaded schist and was exposed at the old surface. Such a condition exists between 16 Shaft and Irwin Shaft, as shown on Figures 2 and 8. Here the covering of schist over the granite thins, or is actually absent in places. Pre-Roan ridges and hills led to thinning or even to non-deposition of the Footwall Quartzites, so that in these places the orebody and granite are in juxtaposition (Fig. 4). This effect simulates granite intrusive into the Roan Group, and it was a decade after underground development began before

exposures demonstrated beyond question that the Roan-granite contact is sedimentary.

The mistaken interpretation of an intrusive granite during the early days of surface mapping was due not only to the feature described, but also to the fact that the granite is non-uniform in character. The "younger" granite was naturally suggested as a possible source for epigenetic mineralization. Garlick and Brummer (13) in 1951 gave comprehensive evidence that no post-Roan granite is exposed on either the Roan or the Copperbelt as a whole, a fact now accepted by all geologists familiar with the area.

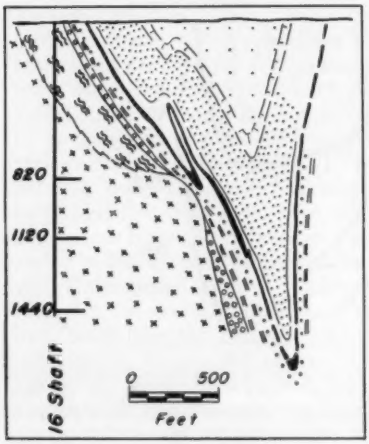


FIG. 4.

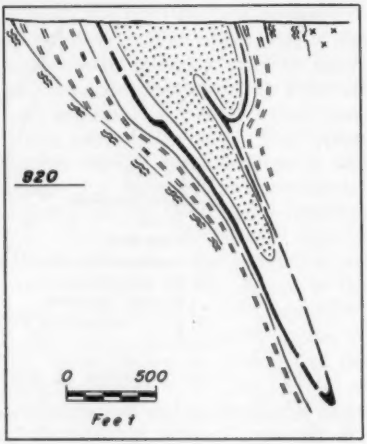


FIG. 5.

FIG. 4. Structure Section 31 showing attenuation of the syncline in the neck area. Note the powerful drag-folding of the relatively incompetent ore shale horizon above a granite hill, leaving the relatively competent bounding quartzites little affected. Note also the basal conglomerate in the low-lying parts of the pre-Roan topography, and the juxtaposition of granite and ore-shale to simulate an intrusive contact.

FIG. 5. Structure Section 36 showing the remarkable attenuation of the syncline in the neck area. This fold has been proved by diamond drilling.

The granite on the Roan is important still in understanding the geology of the syncline, as the hard knobs it forms in the softer schists exercised a profound structural control during folding. This control affected not only the physical shape of the syncline but also certain features of the ore important to genetic interpretation.

From the field evidence it seems that the original schists, already seasoned tectonites, were gradually assimilated or replaced by granitic material in an inter-leaving action to produce a contact zone of great irregularity. The granite is typically gray, but in the cupola area (Fig. 8) there appears to have been increased mobility and flux action, giving rise to red granite by every

gradation from the gray, accompanied by xenoliths and pegmatite formation. Contemporaneity of the gray and red varieties is shown not only by such common features as gneissic structure and complex joint systems due to Roan folding, but microscopic examination and chemical analysis demonstrate their identity and place the rock in a large group of alkali-granites on the C.I.P.W. system. The pegmatites, also sheared parallel with granite foliation in highly strained areas and broken by joints of Roan age, are not found in the sediments. This granite is weakly mineralized in places by pyrite and less chalcopyrite either as a fine, sparse dissemination, or as tiny grains with fine-grained biotite and quartz coating joint planes. The disseminated mineralization is arranged along ill-defined dark bands related to recognizable schist remnants or "ghosts" carrying disseminated sulfides. The other type of mineralization is also believed to have been derived from the invaded rocks, which carry widespread pyrite, pyrrhotite and chalcopyrite, possibly by distribution in late fluids. There is no connection between this weak mineralization and the strong mineralization of the ore, unless it be regarded as a possible source, or part of a source, for syngenetic sulfides.

ORE RESERVES AND MAIN WORKINGS [3]

The Roan Antelope is estimated to contain over 100 million tons of copper ore of average grade 3.3 percent copper; the ore reserve of Roan Extension is very conservatively estimated at over 45 millions tons of the same grade. Due to the uniformity of the orebody with regard to grade, thickness, and stratigraphic position, the main factor in the compilation of reserves is accurate structural prediction. Being bedded, the ore is to be found at a fixed horizon and in a disposition imposed by those factors that exercised structural control during folding. The working theory of origin of this bedded deposit may well determine the degree of success attending further search for ore west of Roan Extension.

Mining began at the nose of the syncline, and has progressed westwards and downwards. The main haulageways are driven in the Footwall Quartzites, and are situated on the 820, 1,440, 1,930 and 2,280 foot levels. The main shafts are Storke Shaft, 16 Shaft and 15 Shaft. Beatty Shaft, the first main shaft, has now been abandoned and the equipment moved to Irwin Shaft on Roan Extension.

STRUCTURAL GEOLOGY

The Strained Materials.—The sedimentary column is shown in Figures 3 to 6. Folding of this column would lead to a maximum of movement in the argillaceous members, i.e., the Green Shale and the mineralized zone of the Lower Roan Group. Sandwiched between the arenaceous Footwall Quartzites and the more competent Hangingwall Quartzites, the Roan ore horizon provides an excellent example of a relatively thin and incompetent argillite lying between thicker and relatively competent arenaceous horizons.

[3] Remarks apply to the position in 1947.

The basement varies in competency with its buried topography—where this is flat, the underlying schists are incompetent; where it is hilly, the composing granite is highly competent. During deposition of the Roan sediments, the Footwall Quartzites became well developed, with thick conglomerates, over the flat schist topography and in valleys, but thinned against the granite hills. Over hills, therefore, the overlying ore horizon came to rest very close

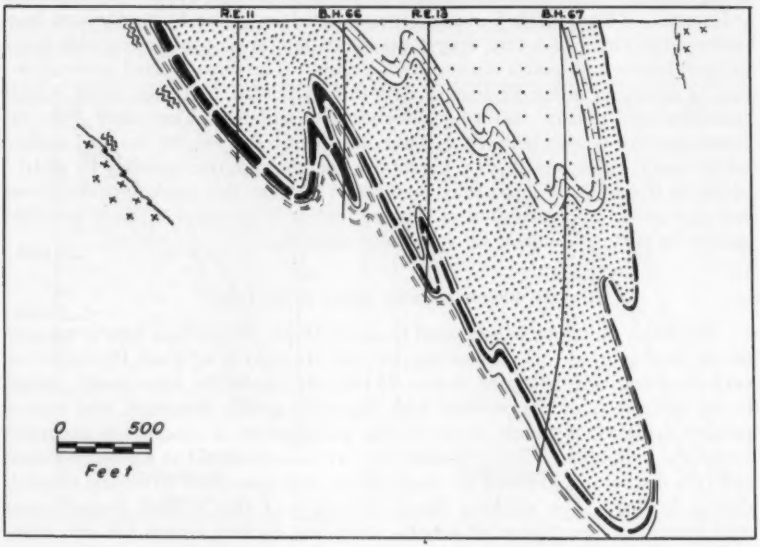


FIG. 6. Structure Section 41 showing the typical conditions on Roan Extension. The section was constructed on the basis of the four drillholes shown.

to the granite basement, a situation in which its relative incompetence under folding stress was increased. It will be seen from Figure 8 that granite ridges trending about N 70° E cross the axis of folding at a high angle.

Major Structures and Control.—Rotational folding stress directed towards about S 30° W is indicated by the general shape of the overturned asymmetrical syncline, the axial plane of which dips steeply northwards. The fact that the southern side acted as a relatively stable block towards which the north side was actively driven is demonstrated by such features as the overturned north limb, compressional thinning of strata in that quarter, more strongly marked gneissic structure in the granite on the north side, and certain conjugate joint sets consistent with such a direction of stress.

During the Roan orogeny the major control of subsidiary fold structures in the sediments was exercised by the heterogeneous physical nature of the basement. The structures illustrated by the maps and sections are easily understood when one visualizes the sedimentary column caught up and

squeezed within the basement complex crumpling beneath north-south compressive stresses.

Westwards from the nose, fold intensity increases in the syncline as it pitches to progressively greater depths and becomes tighter. The north limb is overturned and drag folding becomes important. West of 16 Shaft to about Structure Section 37, the syncline is squeezed into a "neck," and the trough attains a remarkably elongated and attenuated form (Figs. 4, 5). In this neck area, folding occurred transversely across the resistant granite ridges, and the sediments were squeezed between the tightly closing jaws of giant pincers, both laterally and in depth. The incompetent ore shales buckled and flowed by intense drag folding. To the east, the pre-Roan topography becomes flat and the competent granite recedes to leave a massif of cushioning schists. Themselves deforming under stress, they transferred smaller stresses to the Roan sediments, which then folded in a more open way. To the west, the synclinorium of Muliashi was formed, with the highly folded Roan Extension in the intermediate area. Fold axes on Muliashi trend radially from the axial strike of the Roan basin. The more intense deformation of the western parts may possibly be attributed to the fact that the sediments of this area were more deeply buried—the Upper Roan Group is well developed on Roan Extension, and Mwashia is present on Muliashi—than those of the Roan basin.

Nature of Deformation.—Deformation was essentially plastic in character, as shown by three notable structural features. Firstly, the granite mass itself was deformed into a synclinal shape, acutely so in the neck area, accompanied by the development of foliation paralleling the fold shape. Secondly, relief by

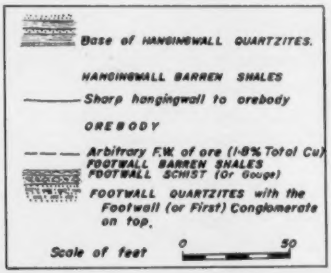


FIG. 7. Diagrammatic section of the ore shale horizon.

transverse faulting is insignificant, being evidenced only rarely and on a small scale in the more brittle quartzite beds. Jointing is, however, well developed in all horizons and probably represents relief from residual strain at a late stage. Thirdly, change in thickness of strata is well marked as thinning on the north limb complemented by thickening in the trough. In certain instances change of thickness is of course due not to compression but to sedimentation, as in deposition of the Footwall Quartzites against ridges. Where the quartzite has covered a granite hill, the normal compaction folding of sedimentation is strikingly accentuated by orogenic compression.

A graphic proof of both compressional thinning of strata and the more intense strain on the north limb is provided by the flattening of conglomerate pebbles. Those shown in Figure 9 came from the north limb, opposite 16 Shaft, interbedded with quartzites intensely recrystallized and minutely fractured by strong squeezing. The pebbles themselves are so thoroughly riddled by minute fractures that they may be disintegrated between the fingers. Pebbles of the same conglomerate on the south limb are normally strong and well rounded. It may be noted in passing that these pebbles indicate the dip as the direction of greatest strain, with the intermediate direction along the strike.

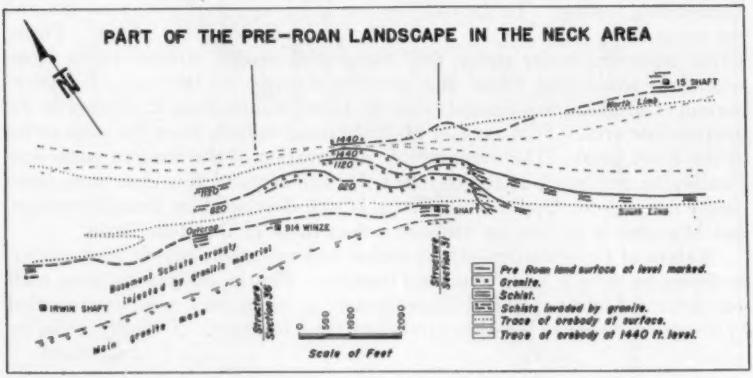


FIG. 8. This figure shows: (1) The pre-Roan land surface forming ridges in the 16 Shaft area; (2) These ridges are formed of granite as opposed to the schist country to the east and schist terrain invaded by granite to the west; (3) The granite forms a cupola in the schists near 16 Shaft; (4) The synclinal folding across the granite ridges produced a pinching action increasing with depth, as shown by the trace of the orebody at the 1,440 ft. level.

Much stress was relieved by movement along bedding planes. The mobile Footwall Schist horizon is prominent in this respect, and on the eastern end it could accommodate most of the slip at the ore horizon. On the western end, however, additional slipping along the dip shows up in the ore shales as bedding faults and narrow but long strike shear zones. Thin incompetent beds in any part of the Roan Group are in places much deformed or even mylonitized. Though cleavage may be developed on the south limb and at the axis, on the overturned north limb the direction of easy movement lay almost parallel with the bedding and neither cleavage nor drag folding developed to any marked extent.

Effects on the Ore Horizon.—The nature of the ore shale changes along the strike as strain intensity varies. To the east, the gently folded argillite is hard and compact. In the dragfolded western zone, the shearing stresses were of an altogether higher order, and led to softening of the ore shales by the

development of schistosity. In places in the neck area the change has gone further, to produce a "veined schist" or "paragneiss." This banded black and white rock consists of elongated fragments of shale interspersed in and veined by calcite and quartz. The effect is probably due to redistribution of these minerals under intense dynamothermal conditions when the shale was liable to cataclasis.

The fold phenomena are accentuated in the relatively incompetent ore horizon, as shown for example in Figure 4, where the bounding quartzites are but little disturbed near violent drag effects in the shales. These drag folds, caused partly by the proximity of granite knobs, occur on all scales

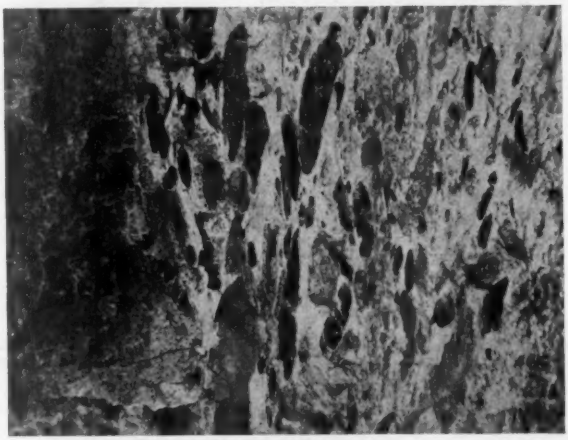


FIG. 9. Photograph showing flattening of conglomerate pebbles on the north limb. From 1,440 ft. level near Section 30, looking west along strike. The larger pebbles are about 6 inches long.

from tiny puckerings to the amazing "16 Shaft fold" shown in Figure 4.[4] Roan Extension drillholes indicate even more striking drag effects, and also the north limb is significantly deformed. With the exception of the big fold mentioned, most drag folding exposed underground to date[5] has simply caused thickening of the orebody (Fig. 10). However, examples have been exposed where drag folds are so tightly pinched that all dips approximate to the normal.

From the axial projection (Fig. 11) it is seen that the economic trough rises in the neck area. Since the orebody was deposited just above the elevation of the ridges, it should theoretically remain approximately horizontal. As the granite ridges closed, the softer sediments were squeezed upwards and

[4] Mapped by A. Cook and the late A. W. Howard. The fold dies away rapidly along the strike in either direction, its length being but little greater than its height.

[5] 1947.

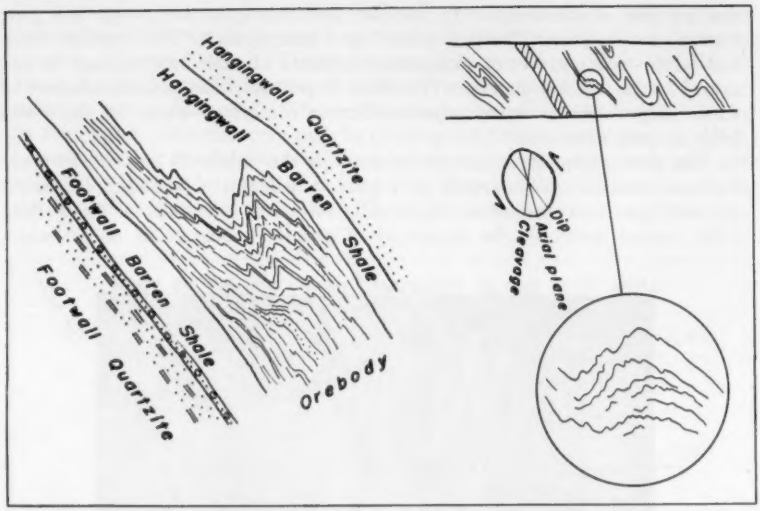


FIG. 10. Typical drag-folding in the orebody. The general section is diagrammatic; the details are from field notes.

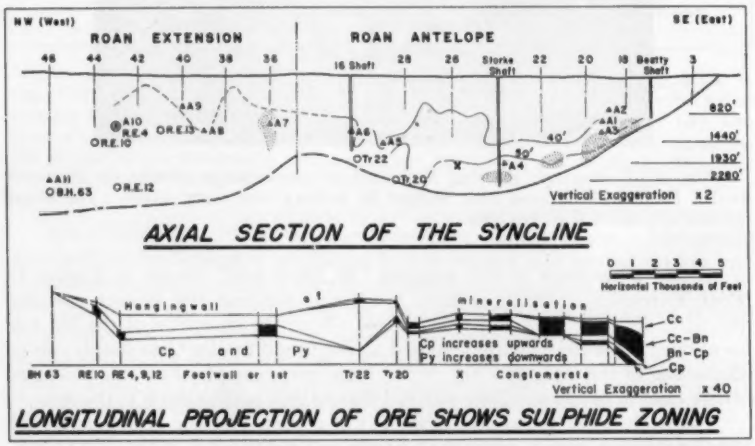


FIG. 11. In the upper Axial Section the lines marked 40 ft. and 50 ft. show stratigraphic thickness from Footwall Conglomerate to the Hangingwall of the orebody, on the south limb. Note how the Hangingwall migrates upwards towards the west. Numbered triangles locate specimens described later. Lower projection shows how the sulfides successively migrate towards the Hangingwall. The diagram is based on the mean of exposures in the stippled areas of the axial section. Where information is based on single boreholes, these are indicated on both sections.

a sharp tongue-like fold formed. Should the trough of the Footwall Conglomerate be plotted, it would probably extend across the area with only a slight upward doming.

Zoning of the Primary Sulfides

The Roan orebody and its extension westwards is characterized by fine-grained disseminated sulfide mineralization. Grain size averages 0.1 to 0.2 mm, commonly varying from 0.001 to 1.0 mm. Within the orebody the primary sulfides, pyrite, chalcopyrite, bornite, and chalcocite, in that order follow

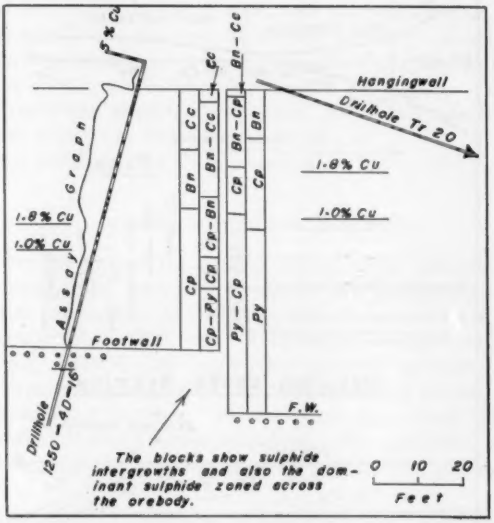


Fig. 12. Diagram showing sulfide zoning in two drillholes 10,800 feet apart along strike. Tr 20 is on structure section 28, 1250-4D-16 is near structure section 18. The dots along the drillholes show where specimens were taken for polishing.

a marked zonal pattern that is slightly inclined to the bedding, in such a way that chalcocite becomes dominant eastwards and towards the hangingwall. In the study of sulfide zoning the "oxide" or supergene minerals offer no complication, as they play an entirely subordinate part in the economic mineralization.

Examination of Figures 11 and 12 reveals the following relationships:

(a) From the Footwall Conglomerate to the hangingwall of the orebody the sulfides follow the sequence, pyrite, chalcopyrite, bornite, chalcocite, so that each is in turn the dominant sulfide, and is overlapped by and intergrown

with the sulfide succeeding it towards the hangingwall. Only in rare instances, and then only for a couple of feet, do three sulfides occur together.

(b) The width and position within the orebody of these zones, and even their presence or absence vary in a regular manner along the strike from the nose of the syncline to Muliashi. Westwards from the nose, each sulfide zone rises across the orebody towards the hangingwall. Thus chalcocite, prominent near the hangingwall at the nose, pinches out near Structure Section 22. Similarly the zone of chalcocite-bornite intergrowths, so important east of

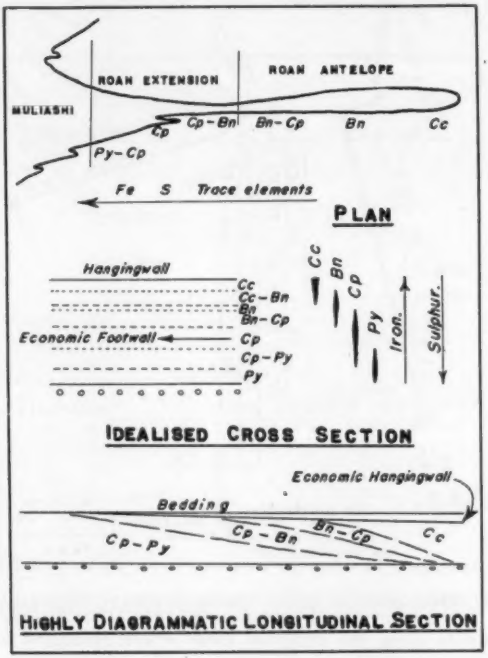


FIG. 13. Diagrams to illustrate sulfide zoning.

Storke Shaft, thins to vanishing point against the hangingwall near the Roan Extension boundary. Borehole 63 on Structure Section 46 shows that bornite, in its turn, has vanished, leaving a mineralization of pyrite and chalcopyrite so low-grade as not to constitute ore. West of this point information is too scant to enable any definite statement to be made. It does, however, appear that bodies of chalcopyrite and bornite are present within the dominantly pyritic beds of Muliashi.

The economic footwall is normally situated within the zone of chalcopyrite, the "Barren Shales" with dominantly pyrite mineralization lying between this

plane and the Footwall Conglomerate. On the nose, however, first pyrite and then chalcopyrite wedge out eastwards against the conglomerate, so that ore grade persists to the base of the shales. This feature is shown in Figure 14. It may be argued that the absence of the yellow sulfides is due to their replacement by bornite and chalcocite. On the other hand, pyrite and chalcopyrite, following the inclined pattern of zoning, may never have been deposited in this area, either syngenetically or epigenetically. Further reasons for favoring the latter alternative will appear later.

The only complication in this simple picture is that on the western half of Roan Antelope and on Roan Extension there exist local thin zones of chalcopyrite and bornite within the pyrite zone, near the conglomerate.

Minor elements in the ore, such as arsenic, antimony, nickel, cobalt, selenium and tellurium, are present in minute quantities only, and increase towards the west. The form in which they are present is not known. The only minor element to assume any importance is cobalt, for linnaeite and carrollite are known to occur in parts of Muliashi and Baluba.

The facts of sulfide zoning are summarized in Figure 13.

MINERALOGRAPHY OF THE ORE

Both the occurrence and the various microtextures exhibited by the sulfides were studied in an attempt to establish their paragenetic sequence and the approximate temperature of formation, and to determine the supergene or hypogene character of the chalcocite. Information was gathered from underground mapping, detailed core logging and polished specimens, which were taken mainly from drill cores (Fig. 12), thus providing detailed data on both zoning and sulfide microtextures. Field evidence was closely linked with that of the microscope for every section examined. No specimens, unfortunately, were available from the worked-out parts of the nose and the higher levels of both limbs.

The most important description and analysis of the microtextures of the Copper Belt sulfide ores has come from Alan M. Bateman (5, 6). In reading the accompanying summary of his conclusions it should be noted that most of his Roan specimens would have come from the eastern end of the syncline, where bornite and chalcocite are dominant.

Mineral	*Interpretation*	*Age*
Pyrite	Scarce. Introduced.	Partly older, partly contemporaneous with chalcopyrite.
Chalcopyrite	Minor. Primary.	Partly older, but generally contemporaneous with bornite.
Bornite	Hypogene if chalcopyrite is hypogene.	Mainly contemporaneous with chalcopyrite.
Chalcocite	Orthorhombic. Mostly hypogene, inverted from isometric chalcocite formed above 91° C.	Partly contemporaneous and partly overlapping bornite; in part later and clearly supergene.
Covellite	Little observed. Supergene.	Late supergene.

Pyrite.—Pyrite occurs in the "barren shales." It is absent on the nose but increases westwards to become the dominant sulfide near Muliashi. Like the other sulfides, pyrite dissemination follows the bedding of the host rock, but the feature is less marked as pyrite grains are larger and more dispersed. In other respects pyrite behaves quite differently from the copper sulfides. Firstly, it is the only sulfide to have a subhedral or euhedral form. Even in the fine-grained ore east of Storke Shaft cubes of 2 mm side are common. Secondly, it is never intricately intergrown with another sulfide, and its association with primary copper minerals is confined to the chalcopyrite-pyrite zone. The two minerals normally occur together as separate grains, the

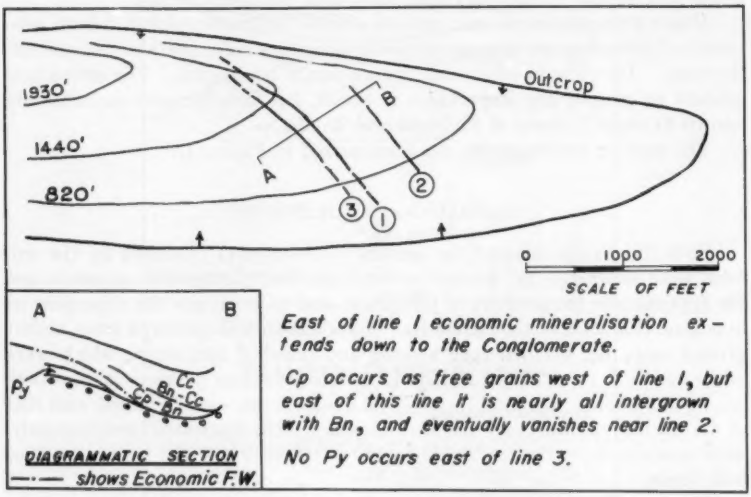


FIG. 14. Plan of the nose of the Roan syncline illustrating how the economic footwall steps away westwards from the footwall conglomerate.

ragged anhedral form of the chalcopyrite contrasting sharply with the well-formed pyrite grains. Less commonly, chalcopyrite abuts on pyrite or partially encloses it. Pyrite in places is replaced by rims of supergene chalcocite, or by hematite. It appears that pyrite is earlier than chalcopyrite, and it may be overlapped by chalcopyrite to some extent.

Chalcopyrite.—Chalcopyrite generally forms a prominent zone, overlapping into the zones of pyrite below and bornite above. West of Structure Section 31 it is the most abundant sulfide. In this highly strained part of the syncline it is more coarsely disseminated than farther east, and in places forms showy "blows" in veins. Throughout the deposit chalcopyrite occurs in the following ways:

(a) *Discrete grains,* irregular in shape, cutting across or fitting between the silicates. Chalcopyrite follows faithfully the bedding of the host rock, and

tends to become coarser as its abundance increases. Sulfide grain-size is commonly proportional to that of the silicates, and there is a general tendency for it to avoid extremely fine-grained beds. Pyrite also shows this tendency, preferring to occupy beds coarsely mineralized with chalcopyrite but avoiding beds carrying only fine-grained chalcopyrite.

(b) *Thread-like stringers parallel to bedding or cleavage* occur especially where cleavage is well-developed. A cluster of threads may venture out along the cleavage direction (Fig. 15A) and swell and pinch in the manner of veins. The same relationships hold for bornite and for chalcopyrite-bornite intergrowths.

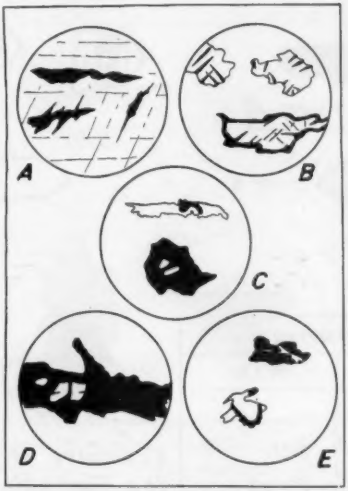


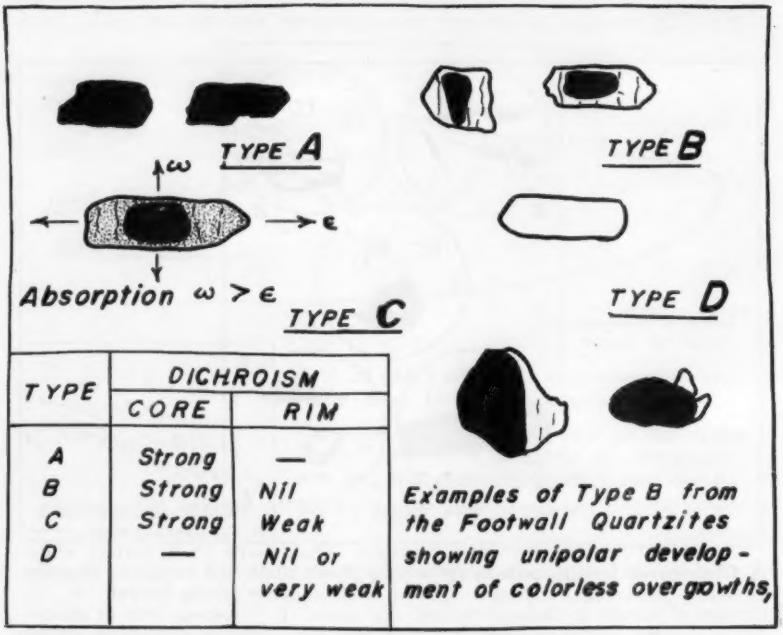
FIG. 15. Drawn from photomicrographs. Chalcopyrite black, bornite white. A. Chalcopyrite forming pods along bedding (horizontal), and occupying cleavage direction. B. Wedges and tapering laths of chalcopyrite cutting bornite. C. Inclusions of bornite in chalcopyrite and vice versa. D. Tapering laths of chalcopyrite piercing bornite included in chalcopyrite. E. Tongues of bornite cutting chalcopyrite and vice versa.

(c) *Intergrowths with bornite* establish the contemporaneity of the two sulfides, as noted by Bateman (6), and are treated in detail later.

Bornite.—Bornite is probably the most important single sulfide of the deposit. It is dominant in the Storke Shaft area and gradually diminishes westward. Bornite is intergrown with both chalcopyrite and chalcocite, so that the zone of pure bornite grains is always relatively narrow. In places the chalcocite extends so far down as to overlap the beds containing chalcopyrite, and then bornite-chalcocite and bornite-chalcopyrite intergrowths occur side by side, with the elimination of the zone of pure bornite. Bornite occurs as listed for chalcopyrite, and its grain-size increases in sympathy with that

of chalcopyrite in folded areas. In addition, and unlike chalcopyrite, bornite is intergrown in various ways with chalcocite.

Chalcocite.—Bateman's account (6) of the occurrence of chalcocite listed the types completely. He regarded only a minor part of the chalcocite as supergene, a conclusion supported by the present work. Chalcocite occurs typically in various intergrowths with bornite, but discrete shapeless grains of pure chalcocite may be found near the hangingwall on the eastern end of the syncline. This resembles the similar occurrence of both bornite and



TYPE	DICHROISM	
	CORE	RIM
A	Strong	—
B	Strong	Nil
C	Strong	Weak
D	—	Nil or very weak

FIG. 16. The types of tourmaline found in the Roan rocks, typified from the ore zone.

chalcopyrite, and, like them, chalcocite also forms little stringers. Discrete grains of chalcocite may also occur below the economic footwall, violating the pattern of zoning. This may be due to supergene action, and the origin of some of the chalcocite near the footwall at the nose (more particularly on the north side of the axis) is open to question. Besides these two forms, chalcocite of supergene environment occurs also as veinlets and larger blebs in places near to and in the Footwall Schist, rims surrounding and replacing other sulfide grains, and cross-cutting ramifying veinlets traversing other sulfides to form a mesh structure.

The chalcocite described above is the normal steely white orthorhombic chalcocite. "Blue Chalcocite" does, however, occur under certain circumstances and will be described later.

Chalcopyrite-Bornite Intergrowths.—Bateman (6) concluded that bornite and chalcopyrite are mainly contemporaneous and hypogene. Davidson (8) considers the Chambishi bornite to be hypogene. Gray (10) states that at

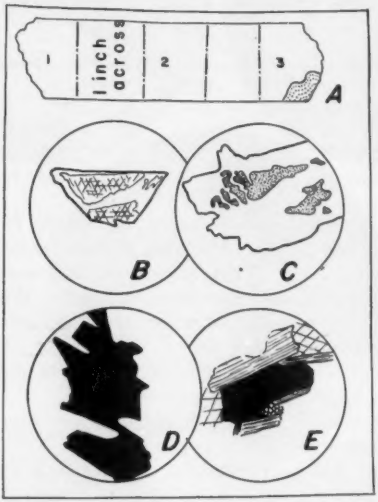


FIG. 17. The Hangingwall contact in borehole Tr. 20. A. Section of split core, borehole Tr. 20, showing position of thin sections. The mineralized portion at bottom right follows drag folding. B. Crystallographic intergrowth of bornite and blue chalcocite (hatched areas) in bornite (white). C. Subgraphic intergrowth of bornite (white) and white chalcocite (dotted). D. Typical sulfide grain-shape. E. Thin section showing the xenoblastic nature of sulfide grains. Sulfide, biotite, carbonate and quartz-feldspar mosaic.

Mufulira these sulfides are possibly contemporaneous, and in places bornite may possibly replace chalcopyrite. Jackson (9) believes that at Nchanga chalcopyrite is primary and that bornite is an intermediate stage in the replacement of chalcopyrite by chalcocite.

Intergrowths of the two sulfides are typically developed in the chalcopyrite-bornite zone, within which chalcopyrite increases in abundance towards the bottom and bornite towards the top. The mutual relationships displayed in intergrowths are consistent over the whole strike length of the ore from the eastern end through Roan Extension. Three basic common types of intergrowth are evident.

1) *Mutual boundary intergrowth* (Fig. 19A) is the typical association of bornite and chalcopyrite found in all parts of the deposit. Most authors

consider that this relationship indicates a hypogene origin by simultaneous deposition. Latsky (14) considers that the mutual boundary association is largely due to unmixing from a solid solution.

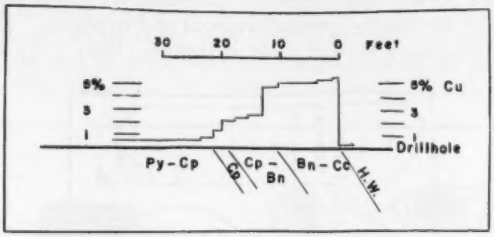


FIG. 18. A typical assay section through the ore of the lower levels at Storke Shaft.

2) *Wedges and tapering laths of chalcopyrite cutting bornite* as in Figures 19A, B, 15B. The chalcopyrite laths tend to form parallel sets, as if controlled by the bornite lattice. They also show reluctance to coalesce with larger areas of chalcopyrite, and to cross each other. Where they do intersect, there is a tendency to contract rather than to swell. All the criteria suggested by Schwartz (18, 20) for recognition of exsolution are met. Scholtz (15) attributes identical intergrowths of bornite and chalcopyrite from the magmatic ores of Pondoland to exsolution.

3) *Inclusions of one sulfide within the other* are rounded to angular in outline, the minor constituent presenting to its host a smooth sharp outline (Fig. 15C). In the chalcopyrite-bornite zone, the more abundant sulfide tends to include the other.

More than one basic intergrowth may occur within the same sulfide grain, and certain other microtextures may be regarded as combinations of two of the basic types (Figs. 19A, 15). The two sulfides may also show completely reversible relationships within a single polished specimen. This intimate association plainly indicates contemporaneous deposition, and an origin by unmixing from solid solution is strongly suggested. This view is further supported by the fact that segregation of the minor constituent to grain boundaries is common, as found in the experimental slow cooling of solid solutions (17). A minor intergrowth is of the same subgraphic type illustrated by van der Veen (22, Fig. 48), who interpreted it as a euctectoid texture.

A later and minor generation of bornite is suggested by textures that may occur in or near zones of supergene action. Replacement of chalcopyrite takes forms such as bornite shreds and veinlets with serrated margins, and oriented tongues of bornite emanating from a fracture and swelling at intersections.

Microscopic amounts of second-generation chalcopyrite also occur under certain circumstances at the loci of replacement of bornite by chalcocite.

At one place in the deposit examples of the "diagrammatic crystallographic intergrowth" of bornite and chalcopyrite were discovered. This intergrowth

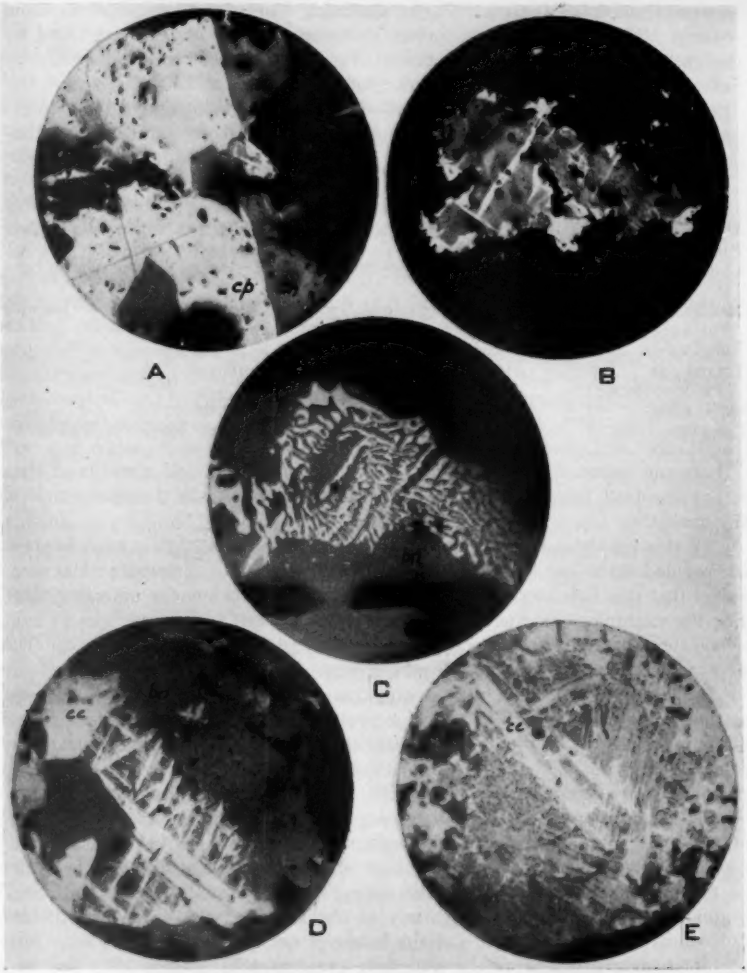


FIG. 19. Chalcopyrite-bornite intergrowth showing mutual boundaries, tapering laths of chalcopyrite piercing bornite and segregation of the minor constituents to the grain boundary of the major. × 230. B. Tapering laths of chalcopyrite in bornite. Sets of parallel laths suggest crystallographic control. × 50. C. Graphic and mutual boundary intergrowth of bornite and chalcocite. × 250. D. A triangular lattice intergrowth of bornite and chalcocite. × 250. E. A lattice intergrowth of bornite and chalcocite associated with inclusions of bornite crowded in the chalcocite. × 270.

was produced by Schwartz (17) by unmixing from a solid solution on rapid cooling. The Roan examples occur in supergene ore, and are regarded by the author as a natural occurrence of the type produced experimentally by Schouten (16) by metasomatism in replacing solutions at 120° C.

Chalcocite-Bornite Microtextures.—Bateman (6) investigated these intergrowths in the Rhodesian ores exhaustively, and his classification and conclusions are summarized below.

Texture	*Origin*	*Interpretation*
Mesh	Supergene	Supergene replacement.
Rim	Supergene	Supergene replacement.
Lattice	Probably hypogene	Hypogene replacement of bornite.
Mutual boundary	Hypogene	Contemporaneity of bornite and chalcocite.
Subgraphic	Hypogene	Doubtful
Triangular Pseudoeutectic	Hypogene	Doubtful
Octahedral	Hypogene	Doubtful
Lamellar	Hypogene	Inverted isometric chalcocite.

Bateman found all the chalcocite to be orthorhombic, and considered that it has inverted from the higher temperature form. Only a minor part of the chalcocite was regarded as supergene.

To this list there might be added a microtexture seen occasionally, formed of crowded shred-like inclusions of bornite in chalcocite. Schwartz (19) considers that this indicates contemporaneous formation below the eutectic point. For the examples examined an origin by replacement is favored. Field evidence suggests supergene replacement in some cases, but in others the criteria of hypogene replacement are adequately met.

It should be mentioned at this point that traces of oxidation may penetrate to the deepest levels on the Roan, due probably to a formerly very low water table. Because of this it has been claimed by some that the Roan chalcocite is supergene, and Bateman (6) himself pointed out that his hypogene interpretation was a minority opinion in 1930. Oxidation occurs in a gross fashion where solutions move freely, but supergene enrichment may also take place at any level along relatively porous beds, where solutions could penetrate in a restricted fashion. Due to a strong control on movement of fluids by bedding in the normally compact rock, this supergene action is very localized and is quantitatively unimportant. Study of chalcocite relationships in both the normal fresh ore and in the various kinds of enriched ore reveals data important to interpretation of the chalcocite problem.

Graphic and mutual boundary intergrowths are by far the commonest chalcocite-bornite relationship. They occur together and grade one into the other via the intermediate stage of subgraphic blebs of bornite in chalcocite. As a sulfide grain is generally made up of unequal amounts of the two sulfides, distinct patches of the major constituent form outside the area of graphic intergrowth, which consists of about equal quantities of bornite and chalcocite (Fig. 19C).

The subgraphic intergrowth is so typical of the Roan chalcocitic ore that if it can be shown to be of hypogene origin, then the greater part of the chalcocite is hypogene. Schwartz (19) pointed out in 1939 that the graphic texture might originate in more than one way, and that "investigations published in the past ten years seem about equally divided between the theory of origin by replacement or by contemporaneous deposition." The intimate association of graphic intergrowth with mutual boundary intergrowths suggests the same origin for both, and Bateman considered that the latter intergrowth indicates hypogene simultaneous deposition. This suggestion of a hypogene origin for graphic texture is strongly supported by field evidence. The intergrowth is found abundantly at depths below 2000 feet in fresh, compact ore. Yet it was never seen by the author in either areas of gross supergene action or in cases of local enrichment of bornite ore along open bedding planes. Since the intergrowth does occur abundantly in areas not subjected to supergene action, and does not occur in those areas where it should if it were supergene in origin, the case for hypogene chalcocite is strengthened. Furthermore, the graphic intergrowth is found abundantly in the ore immediately above the zone of chalcopyrite, which is replaced by chalcocite in very few places indeed. Although chalcopyrite is observed to be more resistant than bornite to the encroachment of chalcocite, if all the chalcocite of the zone above were supergene, replacing bornite to form graphic intergrowths, one should surely expect the attack on chalcopyrite to be fairly well advanced. Finally, the field evidence of sulfide zoning militates against the greater part of the chalcocite being of supergene origin. If supergene chalcocitization were so widespread on the eastern part of the syncline, why should it not be equally well-developed elsewhere?

It is therefore concluded that mutual boundary and subgraphic intergrowths of chalcocite and bornite indicate a hypogene origin for both minerals, probably by simultaneous deposition rather than replacement. This conclusion, then, must apply to the greater part of the Roan chalcocite.

Lattice intergrowths of chalcocite oriented along cleavage directions in bornite are not uncommon, and can often be observed under the oil immersion lens. Though Bateman favored an origin by hypogene replacement of bornite for the Rhodesian ores, both he and Schwartz (19) have pointed out that this microtexture is susceptible of interpretations as hypogene or supergene replacement, or simultaneous deposition or exsolution. Examples are shown in Figure 19D and Figure 19E. The texture suggests replacement to the author. In many cases there is nothing to suggest this is not a hypogene replacement, but in others, supergene replacement is favored. Figure 19E is an example, coming from a small chalcocite vein containing rounded inclusions of bornite. From its position below the chalcocite zone, a supergene nature is strongly suspect. However, lattice intergrowths of bornite and steely white chalcocite were not observed under conditions of gross and undoubted supergene enrichment. Until this intergrowth of bornite and steely white chalcocite in the Roan ore is examined in greater detail, no genetic significance can be attached to it, as it may be formed in more than one way.

In addition, triangular lattice intergrowths of bornite and blue chalcocite are widespread but quantitatively unimportant on the eastern part of the Roan. The microtexture occurs in rock laminae that may be noticeably more coarse-grained than elsewhere, and it may be accompanied by traces of covellite. This intergrowth involving blue chalcocite is probably a result of supergene replacement of bornite. Strong support for this view is gained from study of identical microtextures in enriched bornite ore outside the typical bornite-chalcocite zone. Under conditions of restricted movement of solutions along certain thin porous beds there are microcomplexes involving blue chalcocite and covellite in progressive lattice replacements controlled by the octahedral cleavage directions of the bornite. Blue chalcocite seems to be formed because of retention in the replacing lattice of excess sulfur. This later becomes white, and the chalcocite inherits the isometric bornite structure, as shown by its later replacement by cuprite during oxidation.

The lamellar microstructure, according to Bateman, who agreed with Schneiderhöhn, is that this rare "internal triangular pattern of blue and white chalcocite" denotes a high temperature ancestry. While this interpretation may hold for some examples, others may inherit the isometric structure from bornite that is being replaced in two stages, as mentioned above under Lattice Intergrowths. Söhnge (21) at Messina also reached this conclusion when he discovered bornite relics within the delicate gratings at extreme magnification (× 3000). It appears that no definite genetic significance can be attached to this intergrowth.

Conclusions may be summarized as follows:

Texture	*Interpretation*
Mutual boundary Graphic	Very common, typical of the ore. Almost certainly hypogene. Probably indicates contemporaneous deposition of bornite and chalcocite.
Lattice of bornite and white chalcocite	Replacement of bornite by chalcocite. Hypogene replacement favored, but supergene replacement not excluded.
Lattice of bornite and blue chalcocite	Replacement of bornite by chalcocite, probably supergene.
Lamellar microstructure	Uncertain interpretation. May be either inverted high-temperature isometric chalcocite, or replacement of bornite, supergene replacement favored.
Triangular pseudoeutectic	Rare. Not observed by author. Bateman inclines to interpretation of unmixing at high temperature from a solid solution.
Octahedral intergrowth	Rare. Not observed by author. Bateman interpreted this texture of spicules of bornite octahedrally oriented in chalcocite as hypogene, probably formed above 91° C.
Crowded shreds of bornite in chalcocite	Replacement of bornite, possibly hypogene or supergene.

It is concluded from the study of bornite-chalcocite microtextures that the greater part of the Roan chalcocite is hypogene, generally contemporaneous

with bornite but in part replacing bornite, and possibly inverted from high temperature chalcocite formed above 91 to 105° C. A minor part of the chalcocite is supergene, of much later generation. In places permitting relatively free movement of solutions, chalcocite replaces primary sulfides in rim and mesh textures, but in other places allowing very restricted movement of solutions it typically forms lattice intergrowths of blue chalcocite with associated covellite.

It is not surprising to find that during the period of a low water-table supergene enrichment affected the primary ore in a penetrating fashion. Besides the development of secondary products in relatively open spaces such as the Footwall Schist, enrichment occurred also in the more sandy or porous of the mineralized laminae. The host rock in general, however, proved too compact for secondary action to affect it thoroughly in the time available.

Paragenetic Relationships.—Microscopic evidence indicates essential contemporaneity of the primary copper sulfides, chalcopyrite, bornite, and chalcocite, since bornite is largely contemporaneous with both the others. Bornite may be in part slightly later than chalcopyrite, and chalcocite is probably in part slightly later than bornite. Pyrite appears to be earlier than the copper sulfides, and to be overlapped to some extent by chalcopyrite.

A much later supergene generation involves minor amounts of chalcocite, together with blue chalcocite, covellite and microscopic amounts of chalcopyrite and bornite, all of which are penecontemporaneous.

If the marked pattern of sulfide zoning is due to epigenetic mineralization by an ore-forming fluid, then the fact that the copper sulfides display no notable paragenetic sequence must be regarded as most surprising.

Temperature of Formation.—If the chalcocite is regarded as of isometric ancestry, temperatures over 91° C are indicated. The rare triangular pseudoeutectic intergrowth of bornite and chalcocite was produced by Schwartz by experimental unmixing at 200° C, although lower temperatures may apply in nature.

Unmixing from solid solutions may be accepted for certain bornite-chalcopyrite intergrowths. Schwartz (17) showed that these sulfides form a solid solution above 475° C, while Latsky (14) later demonstrated unmixing from homogeneous material by heating at 220° C at least for 72 hours, a temperature far below that of mixing. Under natural conditions unmixing may possibly occur at relatively low temperatures from homogeneous material.

PETROGRAPHY OF THE ORE

Past publications lean towards a theory of epigenetic mineralization since, among other reasons, the sulfides in their present form are obviously later than the host rock. To account for the bedded nature of the ore and the sharp hangingwall cutoff to mineralization, suggestions have been made regarding possible selective replacement of certain pre-existing minerals, which remain as yet unidentified. Bateman (5, 6), in supporting an epigenetic origin by dilute fluids of magmatic source, early recognized the possibility of sulfide zoning, and suggested that a study of introduced gangue

material, notably tourmaline, might also disclose a possible distributional relationship to intrusive centers.

The object of petrographic examination as conceived at the time of writing is to establish further information on questions of genesis posed by the known features of the deposit. Firstly, regarding the bedded nature of the ore, is selective replacement feasible, and is there any change in the host rock across the hangingwall contact? Secondly, are any (introduced) gangue minerals zoned in sympathy with the marked sulfide zoning, as might be expected from mineralization by introduced fluids? Thirdly, what are the age relationships between the sulfides and the host rock?

In addition to many thin sections of random distribution, a special suite of specimens from the ore zone was studied. This suite was prepared in an attempt to discover possible serial changes along a fixed horizon from east to west with regard to the general nature of ore and host rock, metamorphic effects, and possible zoning of gangue material, notably tourmaline. Locations of the specimens are shown on the longitudinal projection Figure 11, marked A1 to A11. Specimens were taken on the south limb, thirty feet stratigraphically above the footwall conglomerate and as far as possible at the same distance from the trough of the syncline. This distribution should eliminate possible interfering factors arising from random distribution, and decrease possible variations due to change in metamorphic intensity at varying distances from the trough of the syncline. The results of this study are incorporated in the text.

To aid in positive identification and examination of the constituent minerals of the fine-grained micaceous rock, Specimen A5 was mechanically disintegrated and the minerals separated by heavy liquid technique. Results of this examination are also incorporated in the text.

Description of the Ore Shale Horizon

The typical rock is a dark gray, compact and banded mica hornfels of average grain size 0.07 mm, having as its main constituents quartz, alkali feldspars and a clove-brown mica of the biotite family. The minor constituents are apatite, tourmaline, a little zircon, and varying amounts of sericite. Rhombohedral carbonates are generally present. This rock is derived from the metamorphism of a well-bedded feldspathic and calcareous siltstone.

The feldspars are generally orthoclase, microcline and albite in order of abundance. The feldspar, especially orthoclase, is mostly glassy clear, but may also be quite extensively sericitized. The mica present in large amount is uniform throughout the deposit. The color is clove-brown with a tinge of green, and absorption is not as high as in the biotite of igneous rocks. It has the properties: α approximately 1.570; β and γ approximately 1.590; $-2V$ about 12°; Specific Gravity 2.82; it is probably a hydrated member of the biotite series. The colorless mica found in minor amount has the optical properties $-2V$ near 18°, β and γ approximately 1.587 which lie close to those determined for sericite by Mountain (27).

Textural variation from east to west along the strike is due to combinations of the factors of varying metamorphic intensity, degree of stratification and facies change in composition of the ore horizon. Throughout the deposit, however, there persists a basic texture of a compact, fine mosaic of quartz, feldspar and accessory minerals. Although the typical texture is that of a metamorphosed argillite, more intense metamorphism resulted in banded hornfels, and more massive horizons formed typical decussate hornfels. Under high shear stress, schists were formed, and a high carbonate content resulted in calc-mica schists and veined schists.

On the eastern end, a dozen laminae varying slightly in composition and grain-size commonly constitute an inch of rock, and this fine layering of the argillite is accentuated by the bedded disposition of the sulfides. This hard and compact rock consists of the typical granulose quartz-feldspar mosaic, with recrystallized mica flakes showing a preferred orientation. The coarser laminae are lighter in color, being less micaceous than the thinner, more micaceous laminae.

Towards the western part of the deposit the horizon becomes more calcareous, bedding is less accentuated and the grain size of both silicates and sulfides increases. The biotite in these more highly metamorphosed parts has undoubtedly suffered complete recrystallization, and is always present in flakes larger than the quartz and feldspar of the granulose groundmass. In the more massive strata the mica loses its preferred orientation along bedding, and decussate banded hornfelsic textures result. The hornfels may develop spots of cordierite, typically crowded with inclusions. Stronger re-crystallization of the mica under high shearing stress results in schistose textures.

Carbonate content influences the structure rather than the texture of the rock. On the eastern end the small amount of carbonate fits into the general mosaic pattern. On the western end also, it may recrystallize in situ to a coarse mosaic in calcareous beds. Generally, however, the higher carbonate content forms banded calc-mica schists and carbonate veinlets, with the veined schist or paragneiss (mentioned before) as the extreme product. Bands of coarse mica may alternate with bands of the customary fine quartz-feldspar mosaic, the whole broken up by lenticular masses of granular carbonate. Areas of the typical fine granulose groundmass persist, even where the rock appears to be coarse-grained due to recrystallized large grains of mica, calcite and quartz.

The carbonate content of the ore increases from east to west, and the ore at Muliashi is reported to be a metamorphosed dolomitic sediment. Typical analyses are as follows:

	Percent Total Carbonate	Percent Calcite
Typical banded chalcocitic ore from the eastern end. Disseminated carbonate.	3.3	n.d.
Calc-mica schist, structure section 29.	16.1	11.2
Calcareous hornfels, structure section 28A. Disseminated carbonate.	35.9	33.4

The rhombohedral carbonate is mainly calcite, the balance being dolomite except for a minor part that has the optical properties of ankerite of composition 80% $CaMg(CO_3)_2$ 20% $CaFe(CO_3)_2$ (29). Part of the calcite may occur intergrown on the edges of dolomite grains.

Disseminated carbonate invariably displays a grain size larger than that of the quartz-feldspar mosaic, and prefers the coarser, light-colored beds. It appears to fill any available spaces, becoming moulded around silicates or including them poikilitically. In calc-mica schists aggregates of crystals elongated with the schistosity are interleaved with areas of coarse mica and the fine quartz-feldspar mosaic. The carbonate-silicate fabric, as with the disseminated carbonate texture, gives every appearance of either introduction or late recrystallization during metamorphism. The banded carbonate schists, together with little carbonate stringers, are formed in areas of high stress such as the neck of the syncline. The author is convinced that such manifestations of "intrusive" carbonate represent no more than redistribution of original mobile material during metamorphism.

Carbonate may also be associated with quartz and feldspar in concordant lenticular veins. These are dealt with on a later page.

The accessory silicates in the ore horizon are tourmaline, apatite, zircon and white mica. The *mica* normally forms tiny scales of sericite, but in places forms flakes comparable in size with those of biotite. *Zircon* is not as common as the other accessory silicates. *Apatite* is universally present as tiny rounded grains or little prisms. The refractive indices are near 1.630, at the lower limit of the range exhibited by chlorapatite. Specific gravity is near 3.14. The apatite is no doubt detrital in origin, and possibly recrystallized in places.

Tourmaline is ever-present, slightly less abundant than apatite, but resembling it in habit. The quantity of tourmaline does not change either along the strike or across the orebody, but remains fairly constant. The grain size, varying from 0.02 mm to 0.15 mm, is of the same order as that of the other silicates making up the rock. The great interest attached to tourmaline lies in the fact that it is not uniformly pleochroic, but has typically a zone of weakly pleochroic or colorless material surrounding a normally pleochroic central patch (Fig. 16). Although the boundary between these zones is quite sharp, they exhibit optical continuity, and the outer zone of colorless material is clearly an overgrowth on earlier tourmaline. Four types are recognized on the basis of grain shape and composition. Types B and C of Figure 16 are well represented, and types A and D [6] are relatively abundant in the eastern and western regions respectively. It was doubtless to this overgrowth that Bateman (6) referred when he mentioned high-temperature introduced tourmaline grown on original detrital grains. However, it was later shown by Alty (23) in 1933 and Krynine (24) in 1946 that pale or colorless tourmaline overgrowths may form authigenically on the sea bottom.

It is the opinion of the present author that the Roan overgrowths are also authigenic. The genetic importance of the tourmaline is such that the basis of this belief is given in some detail.

[6] Milner (26) notes that apatite may "exhibit dark purple pleochroic cores." Colorless tourmaline is distinguished from apatite of similar form and relief by its higher birefringence.

The dark material of the core is rounded and of the same cold indigo-blue color as Type A tourmaline without overgrowths. This dark tourmaline is of detrital origin. Rounded to angular in shape, or in places elongated parallel with the cross-fractures of the parent grain, its grain size is fairly constant and close to that of the other silicates, particularly the detrital apatite of similar habit and specific gravity. Its color is always the same, identical with that of the tourmaline found abundantly in the pre-Roan rocks. The mineral occurs as discrete grains, never in clusters, large crystals, or "sun-bursts."

Around many of these detrital grains the pale or colorless tourmaline has grown along the c-axis, in places forming perfect little crystals. This material is optically continuous with the dark core, with the same birefringence. Its refractive indices, however, are lower, being 1.623 and 1.640. The mineral is the pure Ca-Mg tourmaline, uvite, the refractive indices of which are given by Krynine as 1.621 and 1.641. Besides support for an authigenic origin from the literature, there are several arguments to support this view. Similar overgrowths are found in all horizons of the Lower Roan Group over a wide area, and the occurrence is unrelated to the sulfides. The Ca-Mg composition, too, is consistent with the presence of Ca-Mg carbonates in the Roan rocks. Besides this, high-temperature tourmaline is normally of a deep color, and it might be expected that tourmaline introduced even in dilute fluids would show some zonal concentration, or grow selectively on certain pre-existent grains.

Notwithstanding this conclusion that the typical Roan tourmaline is in part detrital and in part authigenic, it must be mentioned that tourmaline of high-temperature characteristics exists. Examination of records revealed an exceptional (?) occurrence of the mineral in borehole M.O. 10 (drilled on Muliashi in 1929, Fig. 2) although none was mentioned in the logs of the nearby holes MO 8 and MO 9. In MO 10 (borehole logs by DCS and PKO) change of lithology and a higher grade of metamorphism are noted, and copper mineralization has given way to widespread coarse pyrite. Tourmaline occurs abundantly as black needle-like crystals in biotite schists and gray shales, but most notably as schorl-rock and sun-bursts in quartz veins in the Footwall Quartzites. Niggli (28) remarks that the temperature range "including the pyrite-tourmaline-quartz association . . . represents the transition to hydrothermal formations." However even if further work on Muliashi should confirm the genesis of this tourmaline as hydrothermal, the fact should not be overlooked that such hydrothermal activity does not prove an epigenetic origin for the whole ore deposit.

Comparison of Mineralized and Barren Rocks

The most striking feature of the Roan is the fact that only a part of the "ore shale" horizon is mineralized, and no copper sulfides are found in the similar argillites interbedded with coarser rocks in the bounding formations. Petrographic study revealed no reason for this selectivity of mineralization. All the rocks of the Lower Roan Group are variations on a common theme.

They are all feldspathic sediments, commonly calcareous, and all contain the same clove-brown biotite. Sericitization is common to all, and white mica is in fact more plentiful in the bounding formations than in the ore horizon. All contain the same accessory silicates apatite and tourmaline, both original detrital grains and the authigenically overgrown varieties. The orebody carries disseminated sulfides, and the bounding horizons carry a disseminated iron ore.[7]

The ore shale was compared in detail with rocks closely resembling it in the Hangingwall and Footwall Quartzites, i.e. fine-grained dark gray beds intercalated in the predominantly sandy series. Under the microscope, these rocks resemble the ore shale closely, displaying the same hornfelsic texture and average grain size 0.05 mm. The constituents, both major and minor, are identical, except that the "barren" rocks are more sericitized, and have disseminated specular hematite grains (0.03 mm average size) not so irrregular in shape as the copper sulfides of the ore. Even the carbonate content of hangingwall, ore and footwall argillites analyzed 3.5 percent, 3.3 percent and 3.2 percent respectively. It appears that comparable rocks from the ore shale and from the bounding formations are identical except in their metallic mineral content.

Petrographic study was also made of the abrupt hangingwall contact[8] between "ore shale" and "barren shale" in an attempt to find differences that might account for the presence and absence of sulfides. A specimen of split drill core across the contact, mineralized at one end, is shown in Figure 17A. This rock is a typical hornfels, the contorted and nearly obliterated bedding of which is faithfully followed by the abundant sulfide grains. The whole slice was polished, and thin sections were cut at the three positions shown. The thin sections showed the typical rock conditions in all respects.

Disseminated carbonate grains occur in some beds but not others as the only variation beyond sulfide mineralization, but this variation is independent of the sulfides. The constituents of both ore and barren portions are identical, and no mineral appears to have been either introduced or selectively replaced by sulfide.

The thin section shows this remarkable contact to be so sharply delineated along the bedding that it is possible to run a pinpoint along the boundary between mineralized and barren rock. The sulfide grains are dominantly bornite, with some chalcocite in mutual boundary and subgraphic intergrowth (Fig. 17C) in places. Blue chalcocite lattices also develop in bornite in part (Fig. 17B) and probably represent replacement of some bornite grains in situ.

Sulfide-Gangue Relationships

The "gangue" in this ore is the host rock, which has been metamorphosed. Conflicting claims have been made that the sulfides are an original constituent, that they were introduced contemporaneously with metamorphism, and that

[7] This appears to be a variety of specular hematite identical with that found in platey growths of a ferric oxide containing titanium in both Hangingwall and Footwall Quartzites, and in concordant veins within these horizons. See Garlick and Brummer, idem.

[8] This is reflected by assays, as shown in Fig. 18.

they were introduced after folding of the beds. As the sulfides are obviously not original detrital grains, the syngenetic school claims they were reconstituted to their present habit during metamorphism, simulating introduction during metamorphism, but retaining the original bedded disposition acquired during sedimentation.

The copper sulfides all display, in the general case, extremely irregular shapes. The precise relationships between the fine-grained silicate mosaic and the sulfides are not easy to see, but it is plain that sulfides may cut across and replace silicate grains. Yet sulfide grains may also fit between silicate grains rather than replace them either discriminately or indiscriminately. From the central mass of a sulfide grain short tongues may venture out between neighboring silicate grains. Sulfides may also be moulded on, or partly enclose, the silicates. This feature is particularly well displayed where hornfelsing has occurred and the grain-size is larger. It is clear that the sulfides either crystallized or recrystallized during metamorphism. Their grain-size is comparable with that of the coarser biotite and carbonate crystals, and their xenoblastic habit (Figs. 17D and 17E) shows conclusively that crystallization was relatively late. In other words there is nothing to preclude pre-metamorphic mineralization. During petrographic study a strong impression was gained that the sulfides crystallized contemporaneously with metamorphism, and display in general a xenoblastic habit. In the strongly strained western part of the deposit sulfide grain-size increases generally, and sulfides may form lenticular pods aligned along the bedding or the schistosity, which develops parallel with the bedding. Sulfides may also be aligned across the bedding, following lines of weakness of the fracture cleavage (Fig. 15A), in which case they cut across and replace the silicates. Such replacement probably occurred during metamorphism, the sulfide being introduced either as new material or redistributed from a pre-existing source.

Pre-folding mineralization is supported by the fact that sulfides follow bedding even where it is highly contorted. In the example of a hangingwall contact described earlier, for instance, this is the case. If the mineralization were post-folding and metamorphism, this would be most unlikely, as the rock is uniform across the contorted contact, the bedding is partially destroyed by hornfelsing, and the sulfides in fact occupy the finer-grained of the beds at the contact. Further support is found in the fact that there is no increase in values at the neck or other folded areas. There is no preferential mineralization of deformed, fractured or sheared zones to support late mineralization.

Pyrite is generally subhedral or euhedral, at the expense of all other minerals, and there is no structural distortion, such as augen folding, of the finer-grained rock about the larger crystals. Pyrite may thus appear to be introduced post-folding and metamorphism. However, chalcopyrite, which is younger than pyrite, is believed to be pre-folding in origin, and it is concluded that pyrite also was a pre-folding constituent that recrystallized during metamorphism.

It is concluded that mineralization is of pre-folding age, and that the sulfides recrystallized during metamorphism together with other rock constituents. In the general case this occurred in situ and relatively late, so that

sulfide grains became most irregular in shape as they found place for themselves among the silicates by fitting between or moulding round them or replacing them. In places of high stress, sulfides also migrated during metamorphism to replace and cut across silicates in veinlets, stringers along cleavage and other places of tensional relief.

Summary

From petrographic study it is concluded that the sulfide mineralization is pre-metamorphism and pre-folding in age, and that this mineralization suffered reconstitution during metamorphism. There is no evidence to support the view that the sulfides attained their bedded disposition by selective replacement of a rock mineral or minerals. The ore horizon is identical in respects other than sulfide mineralization with not only the "barren shale" at the hangingwall contact but with other argillites in the Lower Roan Group, and there is no apparent reason why sulfide mineralization should be so abruptly limited stratigraphically. There is a distinct lack of introduced gangue mineralization, and even sericitization and silicification probably resulted from normal regional metamorphism and are common to all the rocks of the Group. No mineral other than the sulfides shows the least tendency to form a zonal pattern or a serial relationship either across the orebody or along the strike except for normal slight change of sedimentary and metamorphic facies. An exceptional (?) occurrence of introduced tourmaline on Muliashi is noted.

THE ROAN ANTELOPE VEINS

A striking feature of the orebody, in folded areas particularly, is the presence of concordant lenticular veins consisting of coarsely crystallized quartz, pink felspar, and carbonates, with white mica and copper sulfides in places. The veins vary from a few millimeters to a few feet in thickness, and exceptionally may reach lengths of a few score feet. They show no feeding channels, and normally form pods around which the wall-rock bedding passes in augen fashion. Slightly transgressive relations may be displayed in places, and some veins follow fracture cleavage or form saddle reefs in folds. Veins of similar form also occur in the Footwall Quartzites and Hangingwall Quartzites, but these are made up of quartz and feldspar with siderite, anhydrite and titaniferous specular hematite.

A conspicuous feature of these concordant veins, therefore, is that they always consist of materials found in the rocks around them, and do not represent the importation of foreign mineral matter. This characteristic is further instanced by the fact that veins on the western end carry more carbonate than those in the less calcareous argillite of the eastern end, and the further fact that sulfides occur generally only in veins within the mineralized part of the shale horizon.

Though a hydrothermal origin for these veins has been advocated, there is more convincing support for the view that they were generated within the parent rocks under metamorphic influences. Such an origin by "lateral

secretion" has long been advocated by W. G. Garlick [9] and has been published by Garlick and Brummer (13). Their conclusions have the full support of the present author.

A note may be added regarding the sulfide mineralization. The ore shale bordering a vein may be locally recrystallized, but the customary bedded distribution of sulfides is clearly unrelated to vein introduction. The coarse vein sulfides, generally chalcopyrite and bornite, as discrete grains or intergrown as described before, may be moulded on mica of earlier crystallization. Late microfracturing in the process is shown by dendritic tongues of sulfide emanating from larger grains along a common direction, and some even later carbonate may cut through fractured sulfide grains.

REVIEW OF THEORIES OF ORE GENESIS

After discovery of the Roan orebody, a syngenetic theory of origin was immediately attractive because of the bedded nature of the sulfides and the confinement of the ore to the same horizon over at least six miles of strike length. The copper values were also found to be remarkably constant, and analogy could be made not only with the Mansfeld deposit but also with bedded authigenic iron sulfides in black shales in many parts of the world. Yet the weight of geological opinion soon swung overwhelmingly towards an epigenetic theory of origin. The major reasons for this view were that the sulfides were widely interpreted as introduced either contemporaneously with folding or even post-folding; they showed hypogene characteristics, and some intergrowths suggested unmixing from solid solutions at elevated temperatures. A convenient source of mineralizing fluids was provided by the granite then believed to intrude the Roan Group, and the veins found in the orebody seemed to lend support to the view. This theory was later strengthened when the sulfides were found to form a zonal pattern. Lindgren (25) advised caution—"most . . . geologists call the deposits mesothermal, formed by granitic emanations. This theory has apparently not yet been proved. A theory of sedimentary origin with subsequent slight metamorphism cannot yet be wholly discarded. There are no mesothermal deposits in the world which are definitely comparable to these enigmatical South African ores."

Later developments demand a critical review of the rival theories of genesis. This is attempted here by examination of the major pertinent facts.

Source of the Sulfides

The epigenetic theory must rely on an undiscovered source of mineralizing fluids. The only post-Roan igneous body known in the vicinity is a gabbro occurring west of Muliashi, near the Kafue River, and this body has never been seriously advocated as a source of the ore. The Roan veins are of metamorphic origin, and, as pointed out by Garlick and Brummer, ore grade "is in no way dependent on the presence of the veins." A. Cook (unpublished work) held that a hidden igneous source might lie to the west, in which direc-

[9] Oral communication.

tion mineralization becomes coarser, metamorphic grade increases, and tourmaline is more abundant. Veins, if hydrothermal, become more numerous westwards in the syncline. Most important, sulfide zoning points a source in this direction. It is shown later that sulfide zoning is in fact not readily explained by introduced fluids. The other points are due to regional metamorphism. Granite buttresses and deeper burial produced more severe dynamothermal conditions, resulting in coarser sulfide recrystallization and more abundant veins, and the impure magnesian sediments on Muliashi show more striking metamorphic effects than the typical Roan sediments. The tourmaline of Muliashi, however, certainly seems to indicate high-temperature fluids, and should be further investigated.

The syngenetic theory demands a substantial source of copper to account for the heavy mineralization of the Roan and other orebodies. While this source also is not obvious, it cannot be argued that the syngenetic theory is therefore invalid. The basement rocks exposed in and near the mine commonly carry iron sulfides and chalcopyrite, and copper staining is fairly widespread. The source of the copper must be sought anywhere in the ancient shield rocks of the African continent, which may have contributed to the basin of deposition. Copper mineralization of these rocks is by no means unknown.

Zonal Deposition of the Sulfides

Mechanism of Deposition.—The epigenetic theory postulates that the ore fluid, probably of a tenuous nature, was introduced into the ore horizon at some point or points unknown. This fluid penetrated along the bedding for great distances to deposit sulfides as a strictly bedded dissemination, in places following tensional openings such as fracture cleavage or gashes on drag fold axes. The sulfides were zonally distributed outwards from the source, but they were unaccompanied by any gangue mineralization. Deposition over five miles of strike was so uniform that no irregular high-grade or low-grade areas were formed in relation to structural controls. The prevailing temperatures were high enough to produce sulfide intergrowths resulting from unmixing of solid solutions.

The author finds such a mechanism beyond his conception of ore deposition. Many details of the process are difficult to conceive, and not the least among these is the mechanism of the very sulfide zoning which is used as evidence to support the theory.

Figure 20A gives a picture of the very narrow and elongated zone into which the components of zoning both along and across the orebody must fit. Ore fluids depositing sulfides within this strip in a steady fashion would most probably produce not the zonal pattern of the Roan, but something of the type shown in Figure 20B.

It may be argued that a series of successive mineralizing surges along different levels in the orebody would meet the case, as shown in Figure 20C. Starting from the footwall, a strong first phase would carry chalcopyrite far to the east, and successive weaker phases would deposit it farther and farther west, on successively higher levels, as the hangingwall was approached. Born-

ite, similarly, would be precipitated farther and farther west on successively higher horizons as the repetitive mineralizing surges became weaker, penetrating less far for bornite. It is, however, difficult to conceive successive surges of mineralization following such a nice procedure—not only following one part (20–30 feet thick) of the shale horizon, in place after place, but also in each place mineralizing a few beds just, and only just, above the beds previously invaded. In other words the tendency for the ore fluid to move along a bed is many hundreds of times stronger than the tendency for it to cross the

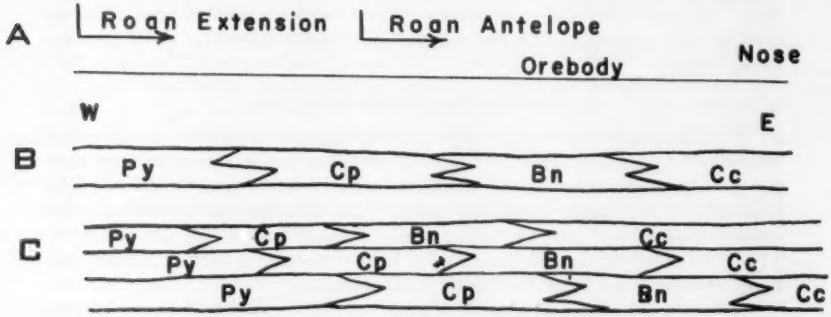


FIG. 20.

beds. The marked control that might be expected to have operated under these circumstances has not been discovered in selectively replaced minerals, a favourable stratum, or any other feature known to the author.

In the case of the *syngenetic theory* details of the process of sulfide deposition must be worked out before the theory can be fully accepted. There are indications of various kinds that the shales were deposited in a water body neither very deep nor of appreciably variable depth. A theory of detrital deposition of the sulfides is untenable for numerous reasons. Copper and iron carbonates precipitated inorganically from sulfate solutions in an alkaline environment might be converted during early diagenesis to sulfides by hydrogen sulfide liberated from organic matter. An inorganic process such as this, in common with a detrital theory, cannot account for either the zoned arrangement of sulfides or the sharp cutoff to mineralization at the hangingwall in homogeneous rock.

There remains a *bacterial origin* for the sulfides. The ore shale is nonfossiliferous, but graphitic material has been detected. Warmth would be a probable requisite for bacterial life. The abundant preservation of feldspar in all the sediments supports an arid environment, and the water body may well have been a shallow continental basin where circulation was restricted and solutes were concentrated by evaporation after being leached from the parent rocks. The liberation of metallic materials under the influence of autotrophic or self-sustaining bacteria is a known but little-understood process. Bacteria such as Leptothrix act in a chemosynthetic way. Leptothrix is

fixing iron at the present time, and was probably doing so in the Precambrian. Cladothrix and Beggitoa are other autotrophs that liberate manganese and sulfur. The precipitation of metallic compounds by the obscure chemical powers of such primeval forms of life might result in colloidal (?) globules of copper and iron sulfides in varying proportions controlled by environment, and thus produce a zonal pattern.

A chemico-bacterial process has in fact been conceived and developed in considerable detail by W. G. Garlick,[10] who has worked out a mechanism to account for both syngenetic sulfide deposition and sulfide zoning on the Copper Belt. Garlick postulates precipitation from stagnant waters by anaerobic bacteria in the presence of organic matter, and claims successful predictive use of the theory.

Stratigraphic Limitation to Ore

The Roan orebody is a part only of a stratigraphic unit, the "Ore Shales." Sulfide mineralization ceases abruptly at some horizon within a uniform rock, for no apparent reason. This sharp economic contact may be followed for hundreds of feet along a bedding plane. On a larger scale, mineralization mounts gradually to slightly higher horizons westwards in the syncline (Fig. 11). No other mineralized horizon is known to exist within the Roan syncline, excepting pyrite in the Upper Roan rocks.

It has been mentioned that no reason has ever been found to explain, on an epigenetic theory, the sharp cutoff to mineralization in homogeneous rock. The epigenetic theory must not only postulate extreme selectivity of an unknown type to account for the sharp hangingwall, but it must also claim that the ore shale was itself so favorable a host rock that none of the bounding formations were mineralized, even though these formations contain argillitic members identical with the ore shale. Again, no reason can be found for the fact that the ore occupies the rock it does, as the ore shale is by no means the obvious channelway for ore fluids (a remark also made by Sharpstone (2) in 1929). An ore-forming fluid would hardly traverse compact shales and mudstones for miles when there exist nearby sandstones, commonly porous and with ill-cemented pebble beds, and a dolomitic Green Shale. It might be suggested that the Footwall Schist at the base of the ore provided a channelway, and the introduced fluids selectively replaced original pyrite in the shales above, therefore not entering the more permeable sandstones beneath. This suggestion is untenable, as pyrite nearest the channelway is not replaced, no unreplaced remnants remain high up in the orebody, and sulfide zoning cannot be explained.

The syngenetic theory is more suited to explain the facts. Ore deposition would begin only when conditions favorable to sulfide-precipitating bacteria were established at some time during sedimentation. The abrupt termination of mineralization is conceivably due to annihilation of the chemo-synthetic bacteria by a subtle change of environment not reflected in the rock. This might possibly take the form of a chemical poisoning or a change of some physical condition such as temperature or even the advent of a predatory organism.

[10] Oral communication.

Hypogene Characteristics of the Sulfides

The sulfide intergrowths are easily accounted for by epigenetic mineralization. The only surprising fact is that in a deposit showing such marked sulfide zoning the constituent sulfides should show no marked paragenetic sequence.

The hypogene character of the sulfides may be explained on a syngenetic theory by reconstitution during metamorphism. This mechanism would also account for the essential contemporaneity of the three primary copper sulfides. It is visualized that chemosynthetic precipitation resulted in complex colloidal materials that formed globules in the sediment. As diagenesis proceeded, these would be squeezed into position among the silicate grains, and form microcrystalline grains compounded of various amounts of copper, iron and sulfur. As temperature and stress increased during metamorphism, these unstable substances would tend to form stable mineral lattices. This resulted in stable sulfide intergrowths of contemporaneous deposition, or the pre-existing homogeneous material unmixed to produce a stable form. This mechanism supposes suitable temperatures, probably greater than 200° C. Deformation by rock flowage indicates fairly deep burial and elevated temperature. The "biotite zone" of dynamothermal metamorphism appears to be applicable, and Harker (30) believes temperatures of 300° C to 500° C may characterize a medium grade of metamorphism. Although Schwartz (17) determined a mixing temperature of 475° C. for bornite and chalcopyrite, Latsky (14) has shown experimentally that homogeneous material will unmix to crystallographic intergrowth at temperatures as low as 220° C. Under natural conditions of prolonged heating and high pressure unmixing temperatures may be even lower. As temperature slowly declined, the constituents of the ore would freeze in the order of their increasing mobility, possibly pyrite, chalcopyrite, bornite, chalcopyrite-bornite, chalcocite, bornite-chalcocite, leaving the later-freezing sulfides free for hypogene replacement of the earlier. The result would simulate pene-contemporaneous hypogene crystallization, with pyrite as the earliest sulfide and chalcocite as the latest.

Other hypogene or "late" characteristics of the ore are explained by redistribution during metamorphism. Carbonate was redistributed, and sulfides migrated to a lesser extent to potential open spaces such as cleavage. The relatively mobile sulfides, recrystallizing with other rock constituents, tended to fill pore spaces and fit between the more stable silicates, inevitably replacing them in places, but also becoming moulded on silicates of earlier recrystallization.

All the facts claimed as more fitting to recrystallization of syngenetic sulfides may be applied equally well to pre-metamorphic epigenetic mineralization. Such mineralization is less likely in the undeformed siltstones, and must still meet the more general arguments against epigenetic mineralization.

CONCLUSION

It is concluded that the most acceptable theory of origin of the Roan ore is that of syngenetic sulfide mineralization modified by dynamothermal metamorphism. All the typical structural and constitutional features of the deposit

observed in the field and under the microscope may be met by this preferred hypothesis. To substantiate the hypothesis firmly, there must be advanced a detailed exposition of the mode of syngenetic sulfide deposition. The adverse evidence of tourmaline of probably hydrothermal type on Muliashi must be further examined and explained.

It is realized that the Northern Rhodesian copper deposits appear to form a class of their own and a challenge that may not meet a united front from geologists for years to come. Yet when universally acceptable answers have been found to the puzzles of the individual deposits, there may then emerge the solution of the larger problem—the genetic history of the whole Rhodesia-Congo border mineral province.

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RADIOACTIVE, PRONOUNCEDLY DIFFERENTIATED PEGMATITE SILL, LAC LA RONGE DISTRICT, NORTHERN SASKATCHEWAN [1]

J. B. MAWDSLEY

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ABSTRACT

Five miles east of Hunter bay, Lac La Ronge, is an irregular pegmatite sill, about 40 feet thick, introuding metamorphosed sediments. It is composed of three facies: an upper margin two inches thick of fine-grained ($\frac{1}{4}$ to $\frac{1}{2}$ inch) oligoclase and quartz; next is ten feet or more of coarse (4 to 6 inches) crystals, chiefly salmon-pink microcline with some peach colored oligoclase, both graphically intergrown with quartz; and, a central band four feet, or more, thick of salmon-pink microcline-perthite crystals up to two feet long with interstial glassy quartz. The same two outer zones are repeated below the central zone.

The central band is not radioactive, but monazite is found in one area in the upper band of the intermediate facies, and uraninite is found in the upper marginal facies and in the immediately adjacent coarse mica schist. At a gable-like part of the upper contact of the sill, over a length of eight feet, and across a width of one to four inches, numerous crystals of uraninite up to one inch in diameter have been obtained. Along the same contact is a similar, but less rich occurrence, and a scintillometer survey obtained a number of above-background readings elsewhere near the inferred upper contact of the sill.

The concentration of the uraninite on the hanging wall of the sill may have occurred partly at the time of consolidation of the marginal facies and partly during the final solidification of the sill.

[1] Presented before the Society of Economic Geologists, Toronto Meeting, November, 1953.

INTRODUCTION

A spectacular but small radioactive occurrence was discovered in the fall of 1949 by Robert B. Ford and Richard T. Claus about five miles east of Hunter bay, Lac La Ronge, Northern Saskatchewan. These students in geology from the University of Wisconsin were on a rapid sight-seeing and prospecting trip through this region. This deposit is about 500 feet east of the east shore of a small lake, locally referred to as Lee or Jahala lake, and is at latitude 104° 16′, and longitude 55° 12′.

In the early summer of 1950 the writer investigating the occurrence and its geological relationship for the Department of Mineral Resources of the Province of Saskatchewan. It is on this field work and some subsequent laboratory work that this paper is based. The detailed part of the work was confined to an area about 1,500 feet square.

S. J. T. Kirkland was the senior assistant who aided both in the field and laboratory investigations.

At present this occurrence is in the group of claims being investigated by Jahala Lake Uranium Mines, Limited.

The paper is presented by the kind permission of the Minister of Mineral Resources for Saskatchewan.

PETROGRAPHIC TYPES

Intermittently exposed in this relatively rocky section of low relief are two rock groups both believed to be of Archean age. The older is possibly part of a highly metamorphosed sedimentary series and the younger a pegmatite sill.

Meta-Sediments

The bulk of the metamorphic rocks in the area investigated is a dark, almost black, fine to medium grained, massive to slightly foliated plagioclase-amphibolite. The texture is a markedly interlocking mosaic of the various constituents. Hornblende, generally containing many inclusions giving it a pronouncedly poikilitic texture, strongly pleochroic from bluish green to straw yellow, forms about 40 percent of the rock volume. The plagioclase is in slightly greater amount and is basic andesine to acid labradorite in composition. Quartz forms 10 to 15 percent and is in grains smaller than most of the hornblende and plagioclase grains. Potash feldspar is either absent or in very small amounts as minute particles. Apatite, magnetite, and sprawling grains or wedge-like individuals of titanite are accessories. In a few slides a few wisps of pleochroic, brown to straw yellow, biotite were noted. The little alteration present is confined to the plagioclase feldspar, which locally is spottily altered to what in the main is a fine, flaky, high-birefringent mineral, either talc or sericite.

Pegmatite Sill

The pegmatite sill varies in thickness but possibly averages about forty feet. There are three distinct and easily recognizable facies,—a border, and

intermediate and central. The best and most extensive exposure of the border and intermediate types has to do with the upper part of the sill. The corresponding parts below the central section are therefore not as well known, especially the lower border facies which was only seen in one locality.

Border Facies.—The border facies of the upper contact is well exposed in the strippings and trenches in the vicinity of the main radioactive occurrences. It has a thickness here of one to two inches, is medium to coarse grained, one eighth to less than half an inch, and almost white in color due to light peach,

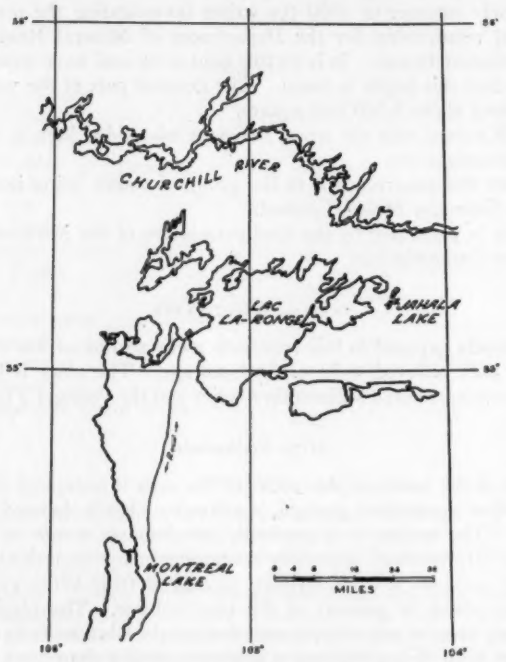

FIG. 1. Geographic location of deposit near Lee or Jahala lake.

or faintly pink, plagioclase feldspar and glassy quartz. With the exception of a little biotite, ferromagnesian minerals are almost absent. The plagioclase generally forms 60 to 70 percent of the rock volume, and is commonly basic oligoclase, but some tested is oligoclase of intermediate composition. All is twinned in accordance to the Albite law. Carlsbad twinning is not uncommon and what is believed to be Pericline twinning is occasionally present. Potash feldspar forms negligible amounts of this facies but in one specimen noted it forms five percent of the rock volume. In this case irregular ragged grains and small rods and grains associated with secondary minerals are centrally

located in relatively large plagioclase crystals. Quartz may amount to as much as 50 percent. It always shows pronounced strain and minute inclusions in trains. It strongly embays and tongues into the feldspar grains, some of which are riddled by small rods and grains of quartz. This poikilitic texture may be due to a contemporaneous intergrowth of the two minerals, but is believed to be a form of replacement by quartz. Apatite, magnetite, and a little zoisite are accessories. The little alteration present is confined to the plagioclase feldspar, which is spottily saussuritized. Most of this is a colorless, high birefringent mineral probably sericite. A little chlorite is also present. A few minute tension cracks containing biotite were noted in the feldspar in one thin section.

At some other localities this fine-grained facies is not present at the contact or is difficult to differentiate from the underlying facies. At a couple of places the feldspar at the contact is quite coarse, reddish-chocolate in color and associated with much biotite. It is somewhat altered basic oligoclase.

Bordering the contact with the plagioclase-amphibolite is a selvedge from a fraction to two or three inches thick almost wholly biotite. The biotite flakes vary in size but are generally an eighth to one quarter of an inch across. They have no preferred orientation. They commonly have minute inclusions with dark pleochroic haloes.

Intermediate Facies.—The intermediate facies in the upper part of the sill is generally ten feet thick and may be as much as 20 feet in places. The lower part is not as well exposed but is presumably of like thickness.

It is petrographically a typical graphic intergrowth of feldspar and quartz. The feldspar crystals are mostly four to six inches in a diameter. The quartz rods differ in thickness in different parts, and even in adjacent crystals, but are rarely more than two millimeters thick and generally have half this dimension. Both light peach or light pink oligoclase and darker salmon-pink microcline are present; the microcline greatly predominates. In places parts of some of the microcline crystals are devoid of the micrographic quartz rods and in others the rods are sparse and far apart. The microcline contains perthitic rods of plagioclase. Some of the oligoclase is acid but most tested is intermediate to basic. Biotite is irregularly distributed in places forming as much as 15 percent of the rock volume, but generally it is in much less amounts. It is commonly arranged in long plates as much as a foot or two long, and gives the impression of having crystallized early. Glassy quartz is locally prominent and may be in masses up to six inches long. Its boundaries with the feldspar are ordinarily fairly straight, but it is definitely interstial. Where there is considerable interstial quartz, muscovite is generally closely associated, and plates of it may be three inches in diameter. Locally magnetite aggregates up to an inch in diameter are present, and are mostly weakly radioactive.

Central Facies.—Where exposed, the central part of the sill is four or five feet in thickness. Its boundary with the intermediate facies is of necessity not sharp but is easily recognizable. This part of the sill is the coarsest and is composed of large crystals of salmon-pink microcline feldspar, the bulk of which are in the neighborhood of two feet long. Perthitic rods of plagioclase in the microcline are general. Glassy quartz forms interstial masses up to a

foot across. Although searched for, no radioactive minerals were found in this central and presumably last part of the sill to consolidate.

The following chemical analysis of this feldspar was made by the Industrials Minerals Division, Department of Mines and Technical Surveys, Ottawa in September 1950.

SiO_2	65.14
Al_2O_3	19.55
MgO	0.13
Fe_2O_3	0.04
CaO	0.20
K_2O	11.38
Na_2O	3.52
TiO_2	0.026
L.0.1	1.11

STRUCTURE

The gneissic and schistose structures in the meta-sediments have low to moderate dips. These structures probably reflect the original bedding.

The upper contact of the sill is very rolling and irregular. In the main it conforms to the attitude of the structures in the intruded meta-sediments and cross-cutting relationships are rare. Parts of the upper contact is exposed in a number of places. What appears to be the lower is seen in the northernmost outcrop mapped. Its relationship to the upper contact exposed to the south is difficult to infer due to the lack of strategically placed outcrops.

The differentiation of the sill into three facies has been previously discussed. The thickness of this banded body is hard to arrive at, it certainly varies but is believed to be in the order of 40 feet.

No faulting or shear, or sheeted zones were seen, and the uranium mineralization is evidently not related to any such feature. Rather, it seems to be impounded by the roof rocks, especially where inverted troughs, or gables, are present.

RADIOACTIVE OCCURRENCES

At the time of the investigation there were three main radioactive occurrences known in this locality and these are indicated on Figure 2 by the letters A, B and C. Besides these, parts of four outcrops were found to be slightly radioactive from twice to, in one case, five times ordinary background; they are indicated by an 'X' on Figure 2.

In the systematic survey of the radioactivity of the area the scintillometer was carried waist high but where radioactivity was present tests were made just off the rock surface.

'A' Occurrence.—Occurrence 'A' is along a short length of the upper contact of the sill where it has a gable-like shape. The roof peak of this gable pitches at a low angle southward, and the erosion of it results in the contact swinging sharply from a south strike to a northeast strike. Fifty feet north of this point of change, the sill contact dips westward under the meta-sediments at 45 degrees. Here over a length of eight feet, radioactivity is very strong but north and south of here the radioactivity quickly drops off. Along the

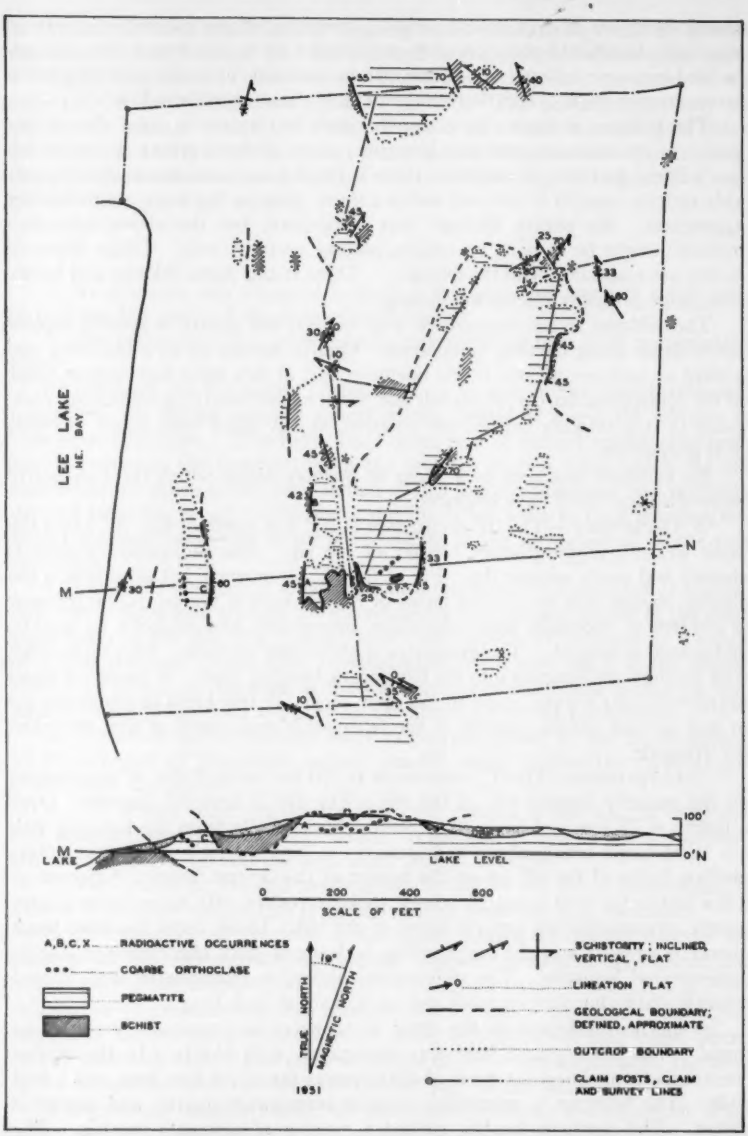

FIG. 2. Plan and section of pronouncedly differentiated, radioactive sill, showing location of radioactive occurrences.

above eight feet of contact and across a thickness of two to six inches are irregularly distributed cubic crystals of uraninite up to one inch to the side imbedded in coarse feldspar, up to one inch in diameter, or in the overlying micaceous contact rock. The thorium content of these crystals is low.

The feldspar is basic oligoclase, chocolate red-brown in color due to fine grains of red material, probably hematite; many of these grains appear to follow a linear pattern. In addition there is much fine micaceous material, probably sericite, most of it oriented and in a linear pattern, but some are in fan-like aggregates. No potash feldspar was recognized, but the above micaceous material might be in part, or wholly, altered perthitic rods. Large flakes of biotite are associated with the feldspar. There is also some chlorite and brown iron oxide probably due to weathering.

The feldspar is not intergrown with quartz, but quartz is seen to replace the feldspar along curving boundaries. Quartz masses up to a foot long and a third as wide are present in the northern part of this eight-foot section, some in the feldspathic border of the sill and some in the overlying micaceous rock. Some of it is roughly banded and mottled, mostly black with minor amounts of it gray-white.

No evidence was seen of a shear or opening along which the radioactive mineralization could have migrated.

'B' Occurrence.—The 'B' occurrence is 200 feet north of the 'A,' along the same westerly-dipping upper contact of the sill. The radioactive section is shorter and much weaker than that of the 'A' occurrence, but otherwise quite similar, except that the border facies of the sill here is typical. The feldspar is reddish to chocolate basic oligoclase, intergrown and replaced by quartz, and biotite is present. The grain-size is about half an inch. This feldspathic rock borders and tongues into the biotiferous hanging wall. A couple of small uraninite crystals were found in the later rock. A few blebs of magnetite up to half an inch across, present in the feldspathic rock, were at first mistaken for uraninite.

'C' Occurrence.—The 'C' occurrence is 250 feet west of the 'A' occurrence, on the easterly-dipping top of the sill. The dip is here 60 degrees. Over a length of 75 feet and from 10 to 30 feet horizontally from the hanging wall are three small areas where radioactivity is high. These are in the intermediate facies of the sill, or on the border of the central facies. Adjacent or a few feet to the west is coarse salmon pink microcline with some coarse glassy quartz, presumably the central facies of the sill. In all these localities black quartz is present and the neighboring feldspar is dark chocolate-red due to disseminated hematite. The radioactive mineral is monazite in well formed crystals, dark chocolate in color and up to half an inch long.

In the northernmost of the three occurrences one monazite crystal was found. The black quartz here was intergrown with biotite. In the central occurrence is an irregular mass of dark quartz up to six feet long and a foot wide. The feldspar is microcline without intergrown quartz, and biotite is absent. The southern locality yielded a number of monazite crystals. The adjacent feldspar is chocolate red in color. Six feet to the north of this pocket

of crystals is some dark quartz dipping east; its hanging wall is altered chocolate-colored feldspar and the footwall is the normal salmon-pink type.

Other Radioactive Occurrences.—There are four minor occurrences, all occurring in the intermediate phase of the sill. The northernmost may be close to the bottom contact of the sill. There is no notable mineralogical characteristic; in addition to the feldspar and quartz there is some biotite mica, except in the southernmost occurrence where blebs of slightly radioactive magnetite is the only dark mineral.

CONCLUSIONS

1. No evidence was obtained indicating that shear or fracture zones controlled the deposition of the radioactive minerals.

2. The pegmatite sill is pronouncedly differentiated into three recognizable facies.

3. Although the pegmatite sill as a whole is rich in the potash feldspar, microcline, the border facies is almost wholly devoid of it and the feldspar is here basic oligoclase. This first consolidated part of the sill would, therefore, hardly represent the composition of the original magma from which the sill was formed. Much of the lime content of this marginal feldspar was probably derived from the invaded sediments, and the latter were at their margins enriched contemporaneously in potash resulting in the formation of biotite-rich selvedges.

4. Lime-rich plagioclase crystallizes at a temperature above that of a soda-rich type. This may account for the relatively fine-grained nature of the marginal facies of the sill, which would have been rapidly crystallized as a result of its composition. This rapid crystallization may have aided in the migration of the potash in this melt to the wall rock, thus materially aiding the formation of the biotite-rich selvedge by the alteration of the hornblende.

5. The above biotite contains many radioactive grains as can be recognized by the presence of pleochroic haloes; possibly some radioactive material migrated with the potash.

6. The quartz occurring locally near the contact of the sill, as irregular and vein-like masses, is probably related to the final consolidation of the marginal facies of the sill and the associated biotite selvedge.

7. The central facies, and presumably the last of the sill to consolidate, is devoid of strongly radioactive minerals such as uraninite and monazite.

8. The presence of uraninite at the upper margin of the sill may be accounted for by: (a) considering that the uraninite present is that forced out of that part of the magma from which the marginal facies of the sill was crystallized; or (b) considering that uranium-bearing fluids migrated to the upper margin of the sill early before any, or little, crystallization had taken place; or (c) that such radioactive material migrated there late at, or near, the time of the consolidation of the final and central part of the sill.

It is generally considered that the radioactive minerals in a pegmatite crystallize out late in the sequence. Also that the euhedral nature of such a mineral as uraninite does not of necessity indicate that it crystallized out first—like

many occurrences of pyrite cubes it may have replaced previously formed feldspar and biotite, the migration of these materials being by some process such as diffusion.

The writer at present favors a combination of the two above stated hypotheses (a) and (c).

9. No adequate reason has been found to explain why in one place in this sill there is a concentration of uraninite and at another a concentration of monazite. However, they appear to be associated with different facies of the sill. The uraninite with the margin and the monazite with the intermediate part.

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Dec. 15, 1953

THE EMERALD, FEENEY AND DODGER TUNGSTEN ORE-BODIES, SALMO, BRITISH COLUMBIA, CANADA[1]

CLIVE W. BALL

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ABSTRACT

The scheelite ore bodies are enclosed within beds of limestone and skarn, which conformably overly argillite, and dip eastwards into intrusive granite. The resultant contact and trough structure are essential for the formation of persistent ore zones. Faulting is found along the main granite contact and minor faults that strike subparallel to the troughs have exercised a definite structural control. Mineralization arising from deep within the granite was distributed by medium of quartz-tourmaline veins and siliceous veins traversing breccia zones and faults. Tungsten solutions were also concentrated by dikes of granite and pegmatite that cut across the trough.

Four distinct types of host-rock are recognized: skarn, limestone, quartz, and greisenized granite. Pyrrhotite and biotite are generally present in the first three types and a close association is shown between scheelite and quartz in all four types. Most of the scheelite is finely disseminated and distinguished only by use of the ultra-violet lamp.

The ore bodies are lenticular and tend to thin and splay out on the flanks. They are contact metamorphic in origin. In close proximity to the ore zones the granite is greisenized. The concentration of scheelite in the contact zone is attributed largely to the processes of greisenization. A genetic relationship is inferred between quartz-biotite veins and scheelite.

The Emerald and Dodger troughs have each been tested over a length of over 4,000 feet, and the troughs follow the general stratigraphic grain of the country.

[1] Presented before the Society of Economic Geologists, Toronto Meeting, November, 1953.

INTRODUCTION

THE Emerald, Feeney and Dodger mines, which are operated by Canadian Exploration Limited, are situated on Iron Mountain, which is seven miles south-south-east of the town of Salmo in south-east British Columbia (Fig. 1). The mine workings extend from 3,800 to 4,400 feet above sea-level and the elevation of the summit of Iron Mountain is 5,200 feet above sea level.

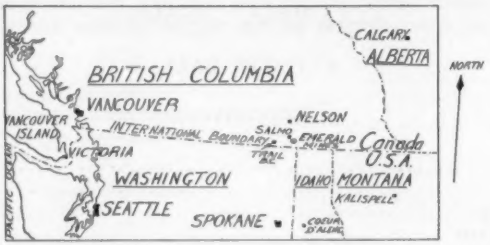

FIG. 1

As a supplier of the strategic ore mineral—scheelite—the Emerald mine has obtained pre-eminence in Canada. The concentrates are remarkably free from deleterious impurities and are in great demand. The geological structure is rather unique in regard to the trough conditions, but the ore associations bear striking resemblances to those of typical tungsten deposits.

History of Mining and Exploration.—Iron Mountain was originally prospected for gold, the old-timers having been attracted to the mountain by the prominent iron-stainings and gossanous showings. From 1907 to 1926, small shipments of high-grade lead ore and lead concentrates were made.

Exploration efforts were renewed from 1938 to 1941 and a detailed geological map was prepared by Mr. Harold Lakes to show all outcrops on the property from the Dodger claims in the north to the Jersey claims in the south. Concentrations of molybdenite were noted in skarn beds on the Dodger claims and examination of samples by the British Columbia Department of Mines, Victoria, indicated the presence of scheelite. Further intensive field studies by Mr. Harold Lakes led to the discovery of high-grade scheelite ore in the contact zone seven hundred feet west of the portal of the old Emerald lead-zinc mine. The interest of the Provincial and Federal Governments was aroused, and following examinations by Government engineers, Wartime Metals Corporation conferred with the Managing Director of Iron Mountain Limited in August, 1942, with a view to developing the property. As no satisfactory agreement could be made, the property was taken over by Wartime Metals Corporation and operated as the Emerald Tungsten Project.

Construction and development work commenced in September, 1942, and in the following fourteen months, the mine was brought to the production stage with a 300-ton concentrator. Then on October, 1943, the war demand for tungsten having eased, the whole operation was closed down. During the six weeks of actual mine operation 132 short tons of concentrates containing 71.07 percent WO_3 and 267 short tons containing 15.07 percent WO_3 were produced.

All mining and other operations on the property remained in abeyance from November, 1943 until early in 1947 when the 47 mineral claims and fractions held formerly by Iron Mountain Limited were purchased by Canadian Exploration Limited. These holdings include the old Emerald lead-zinc mine, the Emerald tungsten mine with its developed reserves, the Dodger showing of scheelite, which had been developed by surface diamond drilling by the Government, and the Jersey showing of lead-zinc ore.

Canadian Exploration Limited commenced operating the Emerald Tungsten mine in June, 1947 and continued to mine and mill tungsten ore at a capacity of about 250 tons per day until December, 1948. During the period 1947–48 an exploration program was carried out which resulted in the discovery of the Feeney tungsten ore zone and the Jersey lead-zinc ore bodies.

In view of the favorable base metal prices and the smaller margin of profit being made on the tungsten, it was decided to close down the Emerald tungsten mine and convert the mill to a lead-zinc operation. The tungsten mine ceased operation in December, 1948, and extensive alterations were made to the mill which commenced operating on lead-zinc ore from the Jersey mine in March, 1949. This operation has continued without interruption to the present day.

In December, 1950, a new tungsten ore body was discovered by deep diamond drilling. A campaign of deep diamond drilling was commenced in 1951 and by widely spaced surface diamond drill holes, tungsten mineralization was indicated over a length of 4,200 feet in the Dodger trough. Closely spaced diamond drill holes at the north end yielded favorable results and the 4,400 Drift South was started in September 1951. In the following month the 4,200 Cross-cut East was started from the hillside and was driven east to intersect the Dodger trough, at a point about 4,200 feet south of the portal of the 4,400 Drift South. Upon intersecting the Dodger trough in the cross-cut, drifting was started northwards to follow under the ore. At this stage the drift has been advanced for a distance of 900 feet and the tungsten ore has been developed by a series of raises and sub-drifts.

The Federal Government early in 1951 purchased two blocks of ground from the Company. These covered the remaining developed ore reserves in selected areas and included the Emerald tungsten mine and the portion of the Dodger trough which had been closely diamond drilled by Wartime Metals Corporation in 1942–43. An agreement between the Government and the Company called for the former to erect and equip a 250-ton tungsten mill, and the Company to mine the ore on a fixed-fee basis. The new mill and an independent camp were constructed adjacent to the 3800-level adit of the Emerald

Tungsten mine and preparations were made to resume production in December, 1951. This was accomplished on schedule.

In September, 1952, the Company bought back from the Government the two blocks of tungsten-bearing ground they had relinquished early in the previous year. The capacity of the tungsten mill has been increased and all of the operations for tungsten and lead-zinc are now controlled by Canadian Exploration Limited.

GENERAL GEOLOGY

Local Structure and Stratigraphy.—The general stratigraphic sequence consists of a series of limestones and argillites that overly quartzites, and are strongly overfolded to the west. The whole series has been intruded by granite.

The oldest rock types on the property consist of quartzites and argillaceous quartzites of the Reno formation, which is of Lower Cambrian age. These beds are followed by brown argillites, which are conformably overlain by limestone beds, which belong to the Laib Group of lower Cambrian age. The tungsten and lead-zinc ore bodies lie within these limestone beds.

The stratigraphic sequence on Iron Mountain is shown in Table I. The granite is post-Jurassic in age. The argillites, schists and quartzites, which lie between the Emerald tungsten mine and the Salmo River, are intruded by

TABLE I

Age	Formation	Estimated thickness	Remarks
Ordovician (?)	Black Argillite	2,500	In fault contact with the Jersey limestone at south end of property.
Lower Cambrian	Limestone	500′ to 1000′+	Emerald and Jersey limestones—part of the Laib Group.
Lower Cambrian	Brown Argillite	500′	
Lower Cambrian	Reno Quartzite	500′	

a boss of monzonite. It is quite likely that this monzonite fills the throat of an ancient volcano, which was partly responsible for the extensive outpourings of andesitic lavas of the Beaver Mountain formation of Jurassic or Cretaceous age, and which covers the western sector of the Salmo map area between longitudes 117°15′ West and 117°30′ West. Similar intrusions of monzonite occur in the northern part of the property, and the lamprophyre dikes which are so numerous in the lead-zinc and scheelite ore zones would appear to be related to the monzonite.

For further details regarding the geology of the Salmo area, the reader is referred to publications by Walker (1)[2] and Little (2, 3).

Folds and Faults.—Strong overfolding to the west is one of the dominant structural features of the Salmo District. By applying this pattern of overfolding, it is possible to interpret the Emerald limestone and the Jersey lime-

[2] Numbers in parentheses refer to References at end of paper.

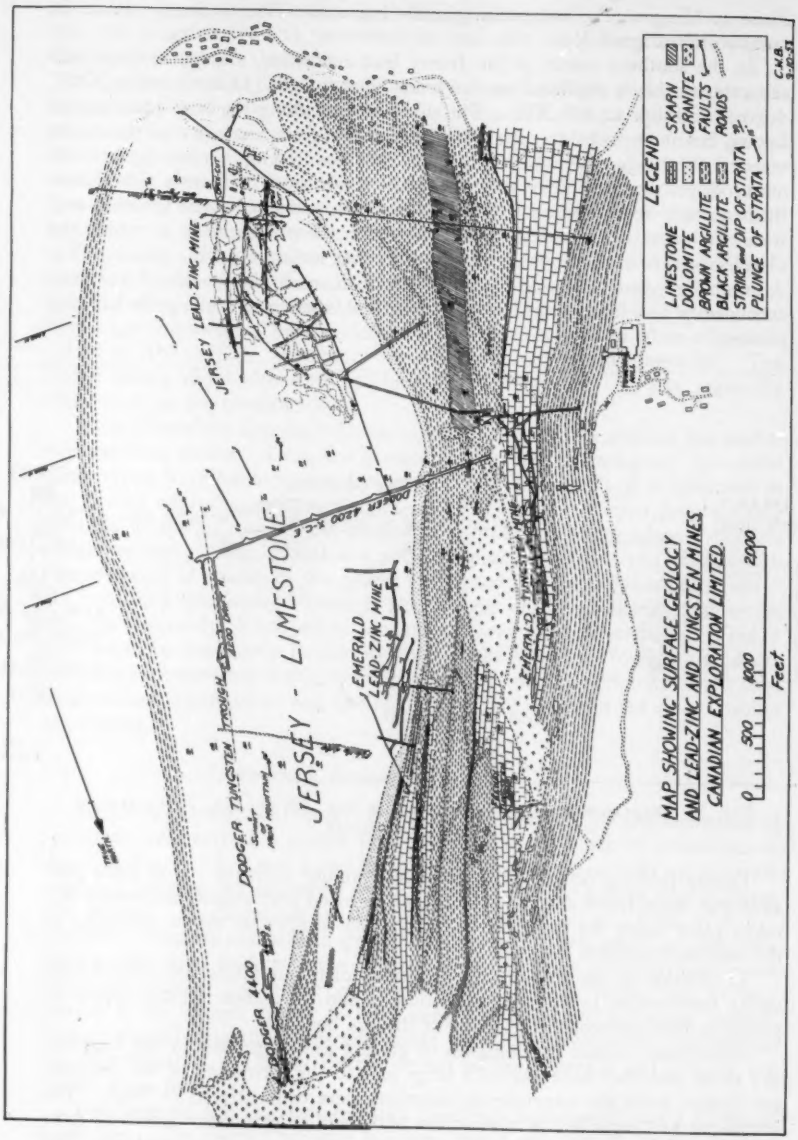
JERSEY - LIMESTONE
JERSEY LEAD-ZINC MINE
DODGER TUNGSTEN
DODGER 4100
EMERALD LEAD-ZINC MINE
EMERALD TUNGSTEN
LEGEND
LIMESTONE
DOLOMITE
BROWN ARGILLITE
BLACK ARGILLITE
STRIKE and DIP OF STRATA
PLUNGE OF STRATA
SKARN
GRANITE
FAULTS
ROADS
MAP SHOWING SURFACE GEOLOGY
AND LEAD-ZINC AND TUNGSTEN MINES
CANADIAN EXPLORATION LIMITED.
300 0 1000 2000
Feet

FIG. 2

stone as being on the same stratigraphic horizon. This is clearly shown in cross-section Figure 3.

In the southern sector of the Jersey lead-zinc mine, a large reverse fault separates the black argillite from the Jersey limestone. The fault strikes N30E degrees and dips at 40° NW. The displacement along the fault plane is not known but it is probably over 1,000 feet. The great majority of the faults mapped in the Jersey mine to-date are steeply dipping normal faults with minor displacement. They strike roughly north-south with east side downthrown; east-west with north side downthrown, and north-west to south-east with north-east side downthrown. There are a few exceptions in which the displacement is in the opposite direction to that indicated in the above series. A number of gently dipping reverse faults with small displacement have been encountered and there is evidence of considerable movement along the bedding planes.

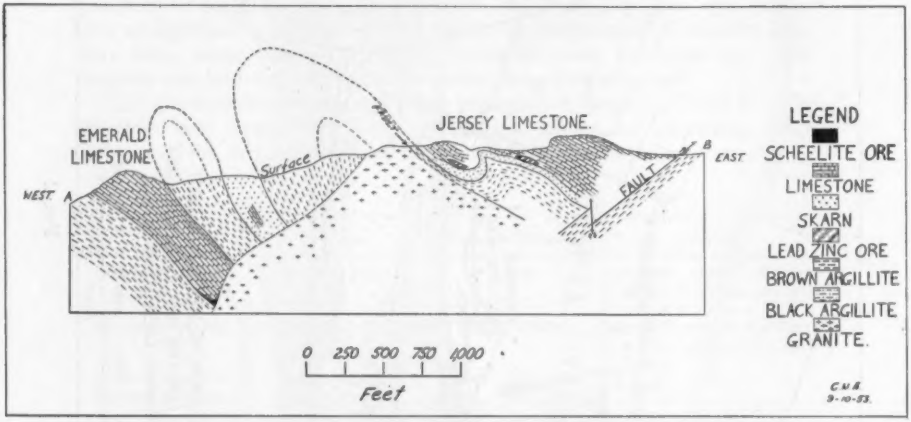

FIG. 3. Diagrammatic cross-section along line *AB* on Fig. 2, illustrating overfolding of strata.

Strong faulting occurs along the main granite contacts. It is quite possible that these faults are pre-granite and renewed post-granite movement has taken place along the fault planes. This has resulted in minor slumping of the sediments against the granite.

In addition to the above, a large number of minor faults and related slips strike sub-parallel to the tungsten troughs and ore zones. They appear in places to have controlled the shape of the ore bodies.

Intrusions.—Dikes and tongues of granite are prominent in the tungsten ore zones and they have played a large part in the formation of the tungsten ore bodies, since the mineralizing solutions were concentrated in them. The intrusions are regarded as concordant and their emplacement seems to have been accomplished by means of a quiet stoping action. Lamprophyre dikes

are extremely abundant and tend to follow along fault planes. They came after the tungsten ore and succeeded the lead-zinc ore mineralization stages. Felsite dikes are not abundant.

Granite.—Granite, which is part of the Nelson batholith, underlies the sedimentary beds and gives rise to a series of crests and troughs that parallel the general structural grain of the sedimentary formations. The granite is generally fine-grained, siliceous, and with a light grey "pepper and salt" appearance. It is classed as a biotite granite. Graphic structure is quite common. The essential minerals are quartz, orthoclase, plagioclase, and biotite. The percentage of quartz varies from 20 to 50 percent, that of orthoclase from 40 to 70 percent. Plagioclase is generally present to the extent of about 10 percent, and biotite varies from 2 to 10 percent. Microcline and perthite have been noted in several sections, and micrographic intergrowths of quartz and felspar are common. The plagioclase has been determined as albite-oligoclase (close to Ab8 AN2). Accessory minerals are apatite and magnetite. The biotite shows slight alteration to chlorite and magnetite. A few pegmatite dikes traverse the granite.

Alteration of the Granite.—In the marginal zones of the granite, the alteration has been active. Thus, the granite borders are characterized by a zone of alteration from ten to twenty feet wide. This is particularly pronounced in the vicinity of the tungsten ore zones. The alteration becomes progressively stronger as the margin of the granite is approached. The felspars become sericitized and the final result is a rock composed of quartz and sericite. A concentration of apatite in the quartz is effected and quartz-tourmaline veins are especially pronounced towards the margin of the granite. A greenish tinge is commonly developed in the granite near the contact zone. This is believed to be due chiefly to chloritization of the biotite. However, in places the greenish coloration is due to the presence of epidote. The alteration with its attendant silicification, was one of the principal agents in the concentration of scheelite.

Emerald, Feeney and Dodger Mines

Structural Control.—Trough structures are essential for the formation of persistent, commercial tungsten ore zones. The ideal set of conditions is shown in Fig. 4. It is noted that the ore occurs in limestone beds conformably overlying argillite and extending with an easterly dip into a steep wall of intrusive granite. Modifications of this simple structure occur (Figs. 5, 6, 7). Numerous tongues and sills of granite and pegmatite are found as offshoots, and granitic dikes that cross the axis of the trough have been responsible for localizing some of the higher grade ore bodies. Minor faults that lie subparallel to the trough appear to have exercised a definite structural control. Trough shaped structures between granite walls have been highly receptive to ore mineralization. This is clearly shown in the Emerald and Feeney ore zones (Figs. 8 and 9).

The Emerald and Dodger ore zones have each been tested over a length of 4,000 feet. The Feeney ore zone has been tested only over a length of about

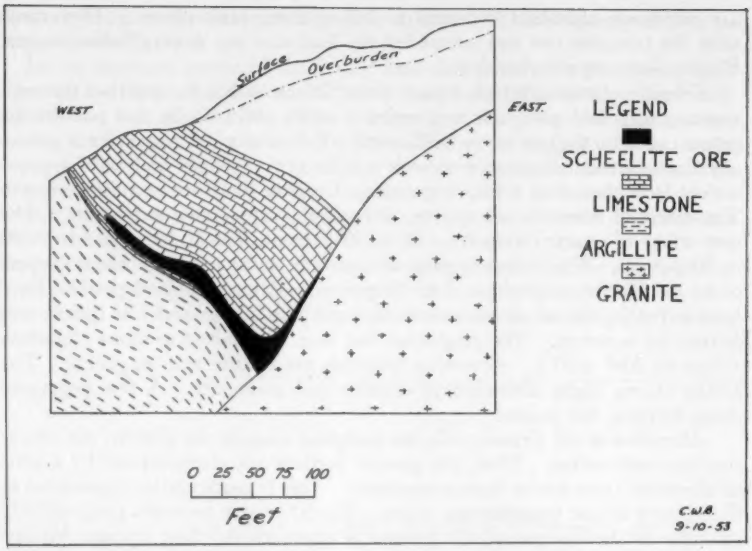

FIG. 4. Cross-section Emerald Mine simplified to show ideal trough conditions.

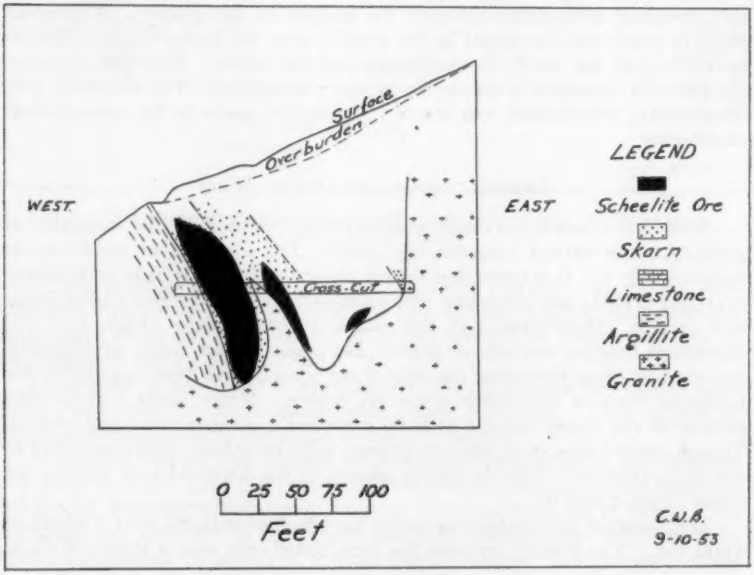

FIG. 5. Cross-section Emerald Mine showing tongue of granite and control by pseudo-footwall of argillite.

250 feet. Overburden has hindered development and testing to the north of the Feeney mine but further exploration is contemplated.

Along the axes of the Emerald and Dodger troughs, a general progressive plunge to the south is evident. For example, the Emerald trough falls in elevation from 4,150 feet at the outcrop to 3,100 feet at a point in the trough about 4,000 feet south of the outcrop. This corresponds to an average south-

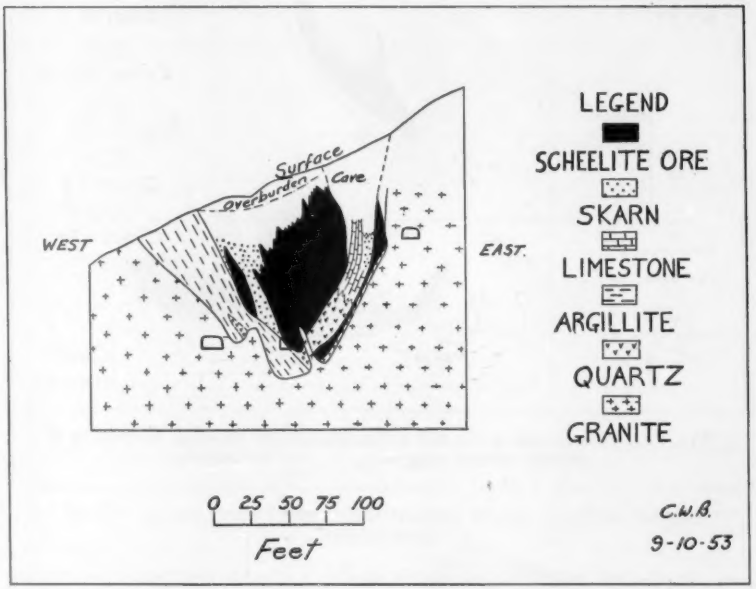

FIG. 6. Cross-section Emerald Mine showing invasion of west limb by granite.

erly plunge of 15 degrees. The average for the Dodger trough is 5 degrees. However, the plunge is by no means regular and numerous sudden alterations and reversals are shown. The strike of the troughs is likewise sinuous.

Host Rock.—Within the Emerald and Feeney ore zones, four types of host rock are recognized: (1) Skarn with pyrrhotite; (2) limestone with pyrrhotite and biotite; (3) quartz with minor pyrrhotite and biotite; (4) altered granite. Disseminated pyrite is generally present to a smaller extent in all four types of host rock.

For the most part, the scheelite ore contains disseminated white scheelite, which is mostly too fine grained to be recognized without the use of ultraviolet light.

The skarn [3] is a hard dense green rock characterized by the presence of

[3] Skarn originated as an old Swedish mining term applied to deposits in Archaean rocks. Goldschmidt (6) and Eskola (7) extended the term to include contact-metamorphic products in younger formations. Tactite is a similar term that is used extensively in the United States.

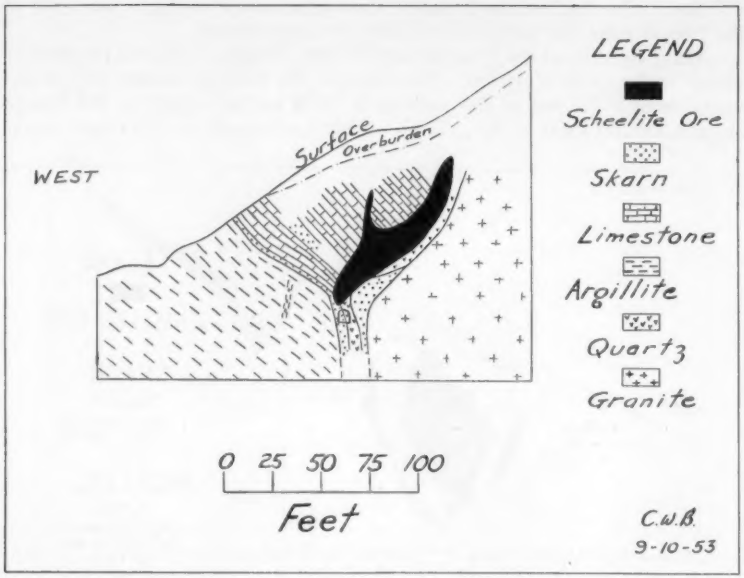

FIG. 7. Cross-section north end of Emerald Mine showing steepening of granite contact suggesting control by faulting.

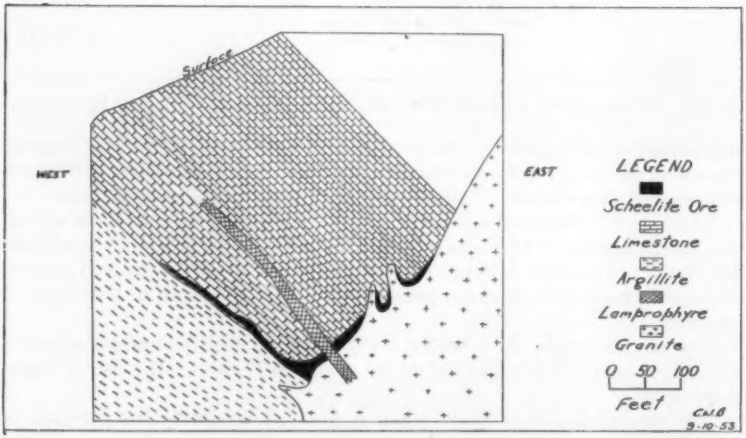

FIG. 8. Cross-section Emerald Mine showing subsidiary troughs in granite on eastern flank of main trough.

quartz, green ferro-magnesian silicates (hedenbergite, diopside and hornblende), and garnet. With increase in the garnet content the rock approaches garnetite. In addition, the skarn in the ore zones generally contains biotite and a little chlorite. Calcite occurs in association with quartz veins. Plagioclase felspar has also been identified as a rare constituent. Cross-fractures in the skarn are commonly filled by quartz veins. Scheelite and molybdenite are generally found in close association with these quartz veins. Two ages of quartz are indicated in the skarn. In the ore zones, the quartz and biotite are

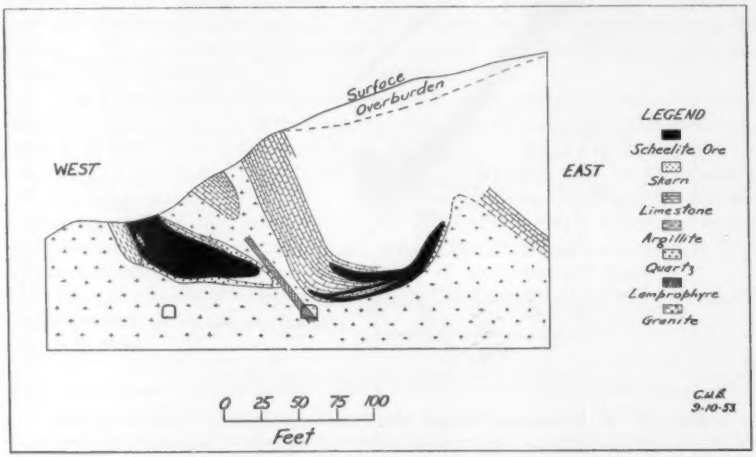

FIG. 9. Cross-section Feeney Mine showing trough structures between granite walls.

closely associated and there is a definite relationship between the scheelite and the quartz and biotite. The pyrrhotite is quite late but quartz-biotite veinlets have been observed traversing pyrrhotite. The pyrrhotite occurs massive, and in anastomosing veinlets.

In the Emerald mine, a large amount of the ore is highly siliceous and consists almost entirely of quartz and biotite or quartz and sericite, with a small amount of pyrrhotite and pyrite. This type of host rock was formed by advanced alteration of intrusive granitic dikes. In the altered granite, which generally forms the marginal zone of the granite body, scheelite is found widely disseminated, and in places a zone up to 20 feet wide is rich enough to be taken as ore. In the Feeney ore zone, the main ore bodies consist chiefly of solid pyrrhotite with biotite and lesser pyrite; nevertheless all four types of host rock are represented. The prevailing host rock of the Dodger ore-bodies is a skarn rock containing pink garnet.

Minor Constituents.—Small amounts of powellite may be prominent in the vicinity of the granite contact and in the skarn zones bordering the argillite. A little molybdenite is commonly associated with the scheelite and quartz in

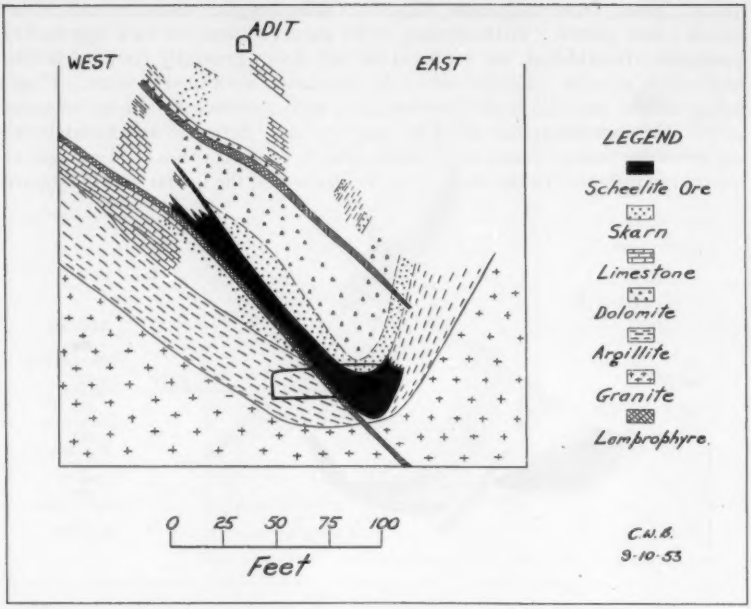

FIG. 10. Cross-section Dodger Mine showing attitude of ore-body and relationship of lamprophyre dikes which follow fault planes.

the skarn at the Emerald and Dodger mines. Insignificant amounts of wolframite have been found in the Emerald and Dodger ore zones but the occurrences are of mineralogical interest only. Scheelite has been formed almost exclusively on account of the excess lime provided by the calcareous strata.

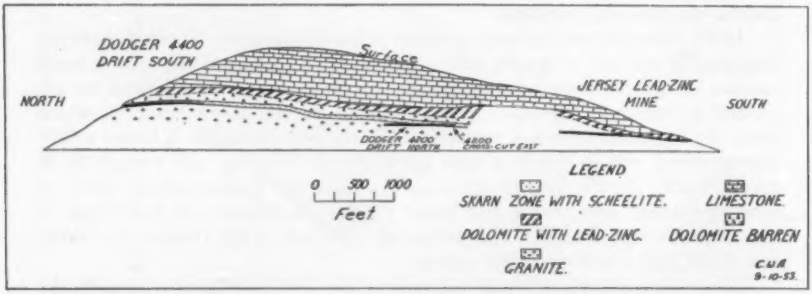

FIG. 11. Diagrammatic longitudinal section showing relationship of Dodger scheelite zone to the lead-zinc zone.

Rare veins of chalcopyrite have been noted in the Emerald and Dodger ore zones.

Localization of the Ore in the Host Rock.—The ore is generally massed in the low point in the trough. The ore bodies tend to be lenticular in cross-section and show a thinning up the flanks (Fig. 4). The ore on the western flank in the southern sector of the Emerald Mine, where the argillite forms a pseudo-footwall is generally more persistent than the ore on the east wall. Control is therefore suggested as having been exercised by the underlying black argillite. Numerous lamprophyre dikes and faults strike and dip parallel to the argillite pseudo-footwall. Another series of faults dip steeply to the west. The limestone, on account of its porosity and ease of replacement, has been highly amenable to scheelite ore mineralization.

The Ore Bodies.—For the most part, the ore bodies are lenticular in cross-section. The thickness is therefore variable, but the maximum thickness low-down in the trough is about 30 feet. The irregular nature of the mineralization, coupled with the lenticular nature of the ore bodies, calls for close control in mining to minimize dilution. The ore bodies show a tendency to split and splay out at their margins. This is illustrated in Figure 10, which is a typical cross-section from the Dodger ore zone. Thus, it is quite common to have fingers of scheelite ore separated by bands of limestone and skarn.

Irregular zones of oxidation are met in the Emerald Mine and caverns are encountered above the ore bodies.

ORIGIN AND LOCALIZATION OF THE ORE

The importance of trough structures has been stressed in the section on structural control. The scheelite mineralization is related to the alteration zone, which forms a zone up to twenty feet wide bordering the main granite contact. The association of scheelite ore with tongues and dikes of granite and pegmatite extending out from the main granite mass has also been referred to. Deep seated fault structures parallel the main granite contact and structural control is effected by minor faults and related slips.

The abundance of quartz in the ore zones and the close association of quartz and scheelite point to the importance of silica in the ore mineralizing solutions. The granite in the contact zone of the Emerald and Feeney mines is riddled with brecciated quartz-tourmaline veins. The tourmaline indicates the role played by boron in the process of mineralization. The element fluorine has also been active in a similar role as evidence the presence of fluorite in zones of fracturing in the Emerald, Feeney and Dodger ore zones.

The presence of biotite in the ore zones is significant. Quartz-biotite veins are noticeable in the ore and a possible genetic relationship is suggested between the biotite and the scheelite.

Kerr (8) in discussing the relationship of tungsten to granitic magmas has referred to the high degree of concentration of minor elements in biotite from both the granites and pegmatites as noted by Shimer. Kerr also states, "Tungsten minerals commonly are associated with mica concentrations in igneous masses or with mica zones along quartz areas. The solutions respon-

sible for the micas could very well be charged with the higher metallic content and in a tungsten-bearing area might be expected to contain this element."

The influence of water in the stage of mineralization is indicated by sericitization of the felspars during alteration and chloritization of the biotite in the granite bordering the contact zone. Water is thus regarded as a prime mineralizer.

ACKNOWLEDGMENTS

The writer is indebted to the Management and Directors of Canadian Exploration Limited for permission to publish this paper. The findings are the result of contributions by numerous workers in the history of development of the Emerald mines. In particular, acknowledgment is made to Mr. Harold Lakes, whose long association with the mines has been a source of inspiration and guidance.

CANADIAN EXPLORATION LTD.,
SALMO, BRITISH COLUMBIA,
Dec. 1, 1953.

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THE GOLD PAN: A NEGLECTED GEOLOGICAL TOOL[1]

JOHN B. MERTIE, JR.

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ABSTRACT

The gold pan is ordinarily regarded as a tool for sampling placer deposits. Another and very important application is shown to be the sampling and study of decomposed bedrock, in regions where outcrops of hardrock are scarce or lacking. This technique was proposed and used by Derby, an American geologist who worked for many years in Brazil. The importance of this method has not been generally recognized, and the writer recalls it to the attention of geologists.

An important application is shown to exist in the study of the decomposed bedrock, known as saprolite, that is so widespread in the Piedmont province of the southeastern United States. Using this technique, two projects have already been successfully completed in this region, and the success attained in both sets a new standard for geological exploration and mapping in areas where saprolite constitutes the dominant type of exposure.

The technique of panning for heavy and semiheavy accessory minerals is described. Types of pans, factors in panning, the operation of panning, and the processing of concentrates in the field are briefly discussed. The gold pan, in the hands of an experienced operator, is shown to be a versatile and efficient field tool, which is completely independent of laboratory facilities.

INTRODUCTION

THE gold pan, in the minds of most geologists and mining engineers, is associated with the prospecting and mining of alluvial deposits. All placer miners know how to use a gold pan, and find it indispensable in their work. The initial prospecting of a placer pay streak, either on gravel bars or in pits and shafts, is done with the gold pan before a sluice box or rocker is used. Prospecting on a large scale is commonly done by drilling, and a panner is always at hand to pan the sludges for gold, platinum metals, or other heavy minerals

[1] Publication authorized by the Director, U. S. Geological Survey, Washington, D. C.

of value. In underground placer mining by drifting, one or more panners are continuously at work at the face, to determine the position and thickness of the pay streak. The gold pan is also used in sampling during mining, in the operation of cleaning up, and in various operations in the gold room. All these uses of the gold pan are familiar to geologists and engineers who are concerned with placer mining, and some of these men become skillful panners.

The gold pan, however, has other applications that are less familiar, and are in fact generally overlooked. The principal of these is the sampling of bedrock, in regions where outcrops of hardrock are uncommon, owing to the decomposition of bedrock by weathering. Such disintegration may be mechanical, chemical, or both; and the products of weathering may either be sensibly in place or they may be residual or eluvial deposits that have moved some distance from their original sites, but still are distinctive of the parent rocks. Most of the heavy and semiheavy accessory minerals of igneous and metamorphic rocks are relatively immune to alteration by weathering; and the character, amounts, and proportions of such minerals afford important clues to the nature of the unaltered bedrock. Therefore, in regions where outcrops of hardrock are uncommon, or perhaps lacking altogether, the study of the accessory minerals becomes an important adjunct to other techniques used in geological mapping. Such work may be done effectively with the gold pan, and is independent of laboratory facilities, as the concentrates may be separated and in large measure identified in the field.

The writer was engaged in geological mapping and general economic geology in Alaska for 30 years, during which time he examined many placer deposits, and became a skilled gold panner. This phraseology is used advisedly, because the panning of gold or platinum metals, and the panning of heavy minerals with densities only a third or fourth as great as the precious metals, require different techniques. When the writer began to work in the southeastern United States in 1943, and saw the scarcity of hardrock and the prevalence of decomposed bedrock, the idea was born of panning these altered rocks for whatever geological or mineralogical information they would yield. But it should be stated that another geologist, Orville A. Derby, had seen this opportunity and had practiced this technique many years earlier.[2] Derby was an American geologist who worked for 30 years or more in Brazil, and published numerous papers in which he dealt with the disintegration of bedrock by weathering, and the application of panning to such weathered products. He tirelessly advocated the use of the gold pan in mapping decomposed rocks, but few American geologists were convinced, owing possibly to the fact that little geologic work was in progress in our southeastern Piedmont province. The writer, 40 years later, takes up the burden of proof where Derby left off.

GEOLOGICAL APPLICATIONS

The most useful geologic application of the gold pan is in the study of weathered igneous and metamorphic rocks in regions were outcrops of hardrock are scarce or lacking. Unaltered rocks of the same kind, however, may

[2] It has also been used to great advantage by Sir Albert Kitson in the Gold Coast.

also be studied by the same method, if the hardrock is crushed and powdered before panning. In southern regions, notably in the Piedmont province of the southeastern United States, the igneous and metamorphic rocks are chemically altered by weathering at most places to depths ranging from 10 to 100 feet. The contact, therefore, between the weathered material and its underlying bedrock is not generally exposed. At many quarries, however, the decomposed bedrock may be seen atop or along the flanks of the hardrock; and by quarrymen this material is called sap or saprock. There appears to be a difference in the meaning of these two terms. Sap is decomposed bedrock that is sufficiently soft to be picked and shoveled, though it is untransported and retains the original texture and structure of the parent rock. Such material is readily removed by a power scraper, in order to reach the underlying hardrock. But at some quarries there is a thick surficial stratum of weathered bedrock that is too hard to be picked and shoveled, and is moved by power shovels only with great difficulty, aided by blasting. This material, which is too much weathered to be usable as road metal and is too hard to be called sap, is designated as saprock. The softer, thoroughly decomposed, earthy but untransported material was called saprolite by Becker (1),[3] who stated that the word was coined from the Greek adjective σαπρος, meaning rotten, although this leaves unexplained the earlier use of the words sap and saprock by unerudite quarrymen. Be that as it may, the word saprolite is a good geologic term, whose meaning is now generally understood.

Rocks may also disintegrate mechanically without marked alteration of the rock-forming minerals, though this process is more commonplace in northern regions than in the southeastern States. In the final stage of such weathering, rocks generally lose their original texture and structure, yielding residual arkosic debris. The term grus or gruss has been applied to such material, but this old German designation has been used with so many other meanings that it is no longer considered to be useful. No well-recognized term is known for such material.

The feldspars of igneous and metamorphic rocks are the minerals that are most vulnerable to decomposition by weathering. Saprolitization, therefore, is a process whereby the feldspars of such rocks are partly or wholly altered to clayey products, and some of the mafic minerals are converted in varying degrees to oxides or clayey materials. Saprolite may also be produced by the weathering of graywacke and feldspathic sandstone or quartzite. Quartz, muscovite, and tourmaline are generally unaltered, and the potash feldspars are more resistant to chemical change than the lime-soda feldspars. Biotite may or may not be altered. Most of the semiheavy and heavy accessory minerals are relatively immune to alteration by weathering; but spessartite is notably susceptible to change, producing brown spots of manganese oxide in the saprolite. Magnetite changes slowly by an increase in the proportion of ferric oxide, and may finally be converted to iron hydroxides. Ilmenite is more resistant to chemical change, but eventually alters to one of several products called leucoxene. Consummation of the alteration of the iron ores rarely occurs in saprolite, but it is a noticeable fact, in the alluvial deposits now being

[3] Numbers in parentheses refer to References at end of paper.

mined in Florida, that ilmenite and leucoxene are at least ten times as plentiful as magnetite, whereas the ratio in the crystalline rocks of the southeastern Piedmont, excepting paragneiss and other rocks of sedimentary origin, is probably closer to 1 : 1. Pyrite rarely survives saprolitization in the southeastern States. Zircon, monazite, and xenotime, the principal minerals that can be used in determining the ages of the rocks, are almost immune to change.

Most saprolites retain the original texture and structure of their parent rocks, such as jointing, sheeting, and other planar structures of primary or secondary origin, as well as lineation and the details of close folding. Owing, however, to a partial solution and removal of some of the products of weathering, saprolite is more porous than its parent rock, and thus a certain amount of compaction may result, though this is commonly of small magnitude. Ordinarily, therefore, little error is introduced by the measurement of structural features in saprolite. In measuring a planar structure in hardrock, it commonly is necessary to measure the traces of the structure on some naturally exposed face, and thereafter to convert the observations by geometrical or trigonometrical means to true strike and dip. Saprolite has the advantage that a face may be cut with a shovel in such an orientation as to obtain directly the desired measurement.

Altered rocks cannot be studied advantageously with the petrographic microscope, because it is impractical to prepare the necessary thin sections. Chemical analyses of saprolite, though valuable in the study of chemical weathering, are of slight value in determining the composition of a parent rock. But the gold pan reveals the nature and amounts of the accessory minerals, which are of high significance, and can be correlated with the petrology. The gold pan also reveals other relations of value. Thus if the feldspars are completely altered to clayey products, and the latter are washed from the pan prior to actual panning, the ratio of the remaining material to that of the original charge will indicate approximately the proportion of feldspar in the hardrock. Or if the plagioclase feldspar is altered to clay, and the potash feldspar is unaltered, their total amounts and relative proportions may likewise be estimated.

Determination of the species of many igneous and metamorphic rocks depends primarily upon the content, character, and ratios of the contained feldspars, if these constitute a high percentage of the modes. Alteration of the feldspars in saprolite renders this system of classification and nomenclature impractical; in fact, the true petrographic designation of a rock reduced to a saprolite may never be learned. But rock nomenclature is fundamentally a method of assembling rocks of like character, and of separating rocks of unlike character, for purposes of classification and geologic mapping. It has been found that rocks of the same species, within the same region, and notably along their regional strike, have closely related suites of accessory minerals. The factors to be measured are the total volume of the semiheavies and heavies, their mineralogical character, and the ratios of the different minerals to one another. Some, or all, of these characteristics may hold over long distances, but in any event they commonly hold for lesser distances, as for example within a single quadrangle. Thus if it is possible at a single outcrop to correlate an unaltered rock with its derived saprolite, it may be possible to carry both the

petrographic and geologic correlations for long distances, without the need of further outcrops of hardrock.

The requirement of at least one correlation between a hardrock and its saprolite merits some explanation. In a rolling country like the southern Piedmont province, bold outcrops of hardrock are uncommon, unless the bedrock is some sedimentary formation that is relatively immune to weathering, such as quartzite. The outcrop of igneous rocks and their metamorphic derivatives are ordinarily saprolite, yet at some places such rocks crop unexpectedly at the surface. These outcrops, which are commonly either flat or somewhat dome-shaped, have been designated by the writer as pavements. The upper surface of a pavement probably represents the lower limit of an ancient ground water table, or at least the lower limit of surficial oxidation in such a table. A pavement was therefore covered originally by saprolite, which in a later physiographic cycle has been partially eroded. The hardrock may be only slightly exposed, producing a flat outcrop of small dimensions; or it may be extensively bared, producing a dome-shaped outcrop, whose size and relief depend upon an earlier configuration of the surface, and the configuration of the underlying water table. Some large pavements, such as that at the quarry at Mount Airy, Surry County, N. C., show little relief; others, like Stone Mountain in De Kalb County, Ga., are conspicuous domes. If uneroded saprolite remains in contact with the hardrock along the flanks of a pavement, this relation will constitute an ideal correlation. Most quarries in the southeastern States are started on pavements, for obvious reasons; and therefore quarries afford good correlation between hardrock and saprolite, if the latter is partially preserved.

Pavements and quarries exist that have no overlying or flanking stratum, either of saprock or of saprolite. At some sites the weathered rock has been completely removed by erosion; at others, it has been removed and replaced by alluvium that somewhat resembles saprolite, but contains waterworn detritus. Commonly such material is streaked and mottled in shades of brown, red, yellow, and green, thus resembling some of the older formations of the Coastal Plain. Some of the quarries southeast of Salisbury, N. C., in the area around Granite Quarry, exemplify this condition. This superjacent cover may be largely reworked saprolitic material, but obviously is quite unsuited for purposes of correlation. To be sure, the accessory minerals may be obtained by crushing and milling the hardrock, and by panning this rock powder. But facilities for such work may not be immediately available, and the writer has found it profitable to use another source of powdered hardrock. At quarries where some or all of the product is road metal, concrete aggregate, or railroad ballast, a deposit of fine rock powder will invariably be found under the jaw and secondary crushers. This is a satisfactory material from which the accessory minerals may be recovered by panning, though the resulting samples of concentrates are qualitative rather than strictly quantitative. The same procedure will also be useful in northern regions, or in recently glaciated regions, where weathered bedrock is lacking.

Two projects in the southeastern States have recently been completed, wherein the gold pan was used on a large scale. First, the Shelby quadrangle,

in Cleveland and Rutherford Counties, N. C., was selected for geologic mapping. Robert G. Yates and William C. Overstreet began this work in 1948, and were joined a year later by Wallace R. Griffitts. The mapping was completed by these three men. Many hundreds of samples of saprolite, eluvium, residual soils, and fluvial deposits were collected and panned in the course of this work, with the objectives of identifying and correlating the accessory minerals of the rocks, and of relating their character and distribution with the eluvial and fluvial placers. No similar methods have heretofore been used on such a scale in the southeastern Piedmont province; and the results obtained by these three men are so outstanding as to set a new standard of excellence for geologic mapping in this region.

The second project is a study of the granitic rocks of the southeastern States, which is still in progress. The primary objective of this work is the correlation of these rocks, and the determinations of their relative and absolute ages, for the purpose of later geologic mapping. An economic byproduct has been the mapping of two belts of monazite-bearing rocks for an aggregate distance of 800 miles across five states. A preliminary report on this exploratory work has been made by Mertie (3). Working alone on the granite project, the writer has collected and panned 516 samples of bedrock, mainly saprolite, aggregating 45,200 pounds, of which 175 samples, weighing 18,400 pounds, were found to contain monazite. This work could not have been accomplished without the use of the gold pan on a large scale.

The preceding data have been presented primarily to recall to the attention of geologists an old but generally unused tool for geological mapping, not only in regions where the rocks are greatly altered by weathering, but also where mapping is ordinarily done from exposures of hardrock. The acquisition of samples of the accessory minerals has two principal objectives: first, to learn the nature and amounts of these minerals, for the value this information will have in correlation and geological mapping; and second, to obtain samples of adequate size of certain radioactive minerals, such as monazite and zircon, that can be analyzed chemically and radiometrically to obtain determinations of age. It should be stressed that these methods constitute merely an additional tool to supplement, and not to supplant, structural observations, petrographic determinations, and chemical analyses.

Geologists who lack experience in the economic geology of placer deposits usually also lack a rudimentary knowledge of the use of the gold pan; and even if they are familiar with gold panning, they probably are unfamiliar with the technique of panning for the accessory minerals of rocks. The writer, though an experienced gold panner, found that quite different methods were necessary in panning for heavy minerals. Therefore, the remainder of this paper will be devoted to an elementary description of the application of the gold pan to such work.

TECHNIQUE OF PANNING

Types of Pans.—Two principal types of containers are used for the concentration of heavy minerals by hand from unconsolidated materials, in the process known as panning (or vanning). These are the batêa and the gold pan,

though others of more primitive form are also used. The batêa is a cone-shaped container, which is said to have originated in Brazil. A similar device in the Malay States is called the dulong, shaped either like a batêa, or as a shallow elongate container. An elongate pan of this kind is also used in India. In Nigeria and the Gold Coast the concentrator is called a calabash, which at some places is similar to the dulong and at others is merely a large semispherical or semispheroidal gourd. The batêa and similar containers are commonly made of some hardwood, as for example the Honduras mahogany in Central America. Wood is preferred to metal, because the resulting pans are cheaper and lighter, and because the rougher surface of such pans is believed to retain fine-grained minerals more effectively than metal pans.

The standard batêa of Brazil has a diameter of about 20 inches, and a depth at the center of 2½ to 3 inches. A batêa of this diameter is shown in Figure 1, alongside a standard gold pan with a diameter of 16 inches. Both have depths of 2½ inches. Batêas, ranging in diameter from 30 to 36 inches, are also used for diamond washing in Brazil and British Guiana, and the same is true of some of the dulongs used in concentrating cassiterite in the Malay States. Derby (2) used a small portable batêa made of copper, with a diameter of 12 inches, and a central depth of nearly 3½ inches. The apical angle was thus 120°, which is smaller by 30° than the corresponding angle of a commercial 20-inch batêa. The batêa is operated initially with a rotatory motion, known as vanning, such that the gravel and sand are discharged over the rim by centrifugal force. The later technique is not unlike that used in a standard gold pan.

Gold pans are made in diameters of 10, 12, 14, and 16 inches, but the 16-inch pan is the standard size for miners and prospectors in the United States, Canada, and Alaska. A larger pan is said by Peele (4) to be used in Australia. The diameter of the base of a 16-inch pan is commonly 9¾ to 10 inches, and the depth 2½ inches. For a 16–9¾–2½-inch pan, as illustrated in Figure 1, the angle between the side and the base is about 141°, which is about 10° less than the apical angle of a 20–2½-inch batêa, but 21° greater than the batêa used by Derby. These angles are determined by local custom rather than by any mathematical formula, and the worker merely learns to use his pan to obtain the best results.

The volume of a 16–9¾–2½-inch gold pan, when level full, is 332 cubic inches, or 0.007 cubic yard, thus making about 143 pans to the cubic yard. If the charge is piled conically to a height of 2 inches above the lip, the corresponding volume is 466 cubic inches, or about 0.01 cubic yard, thus making 100 pans to the cubic yard. If the swell of the charge is taken into account, a larger number of pans must be allowed to equal the cubic yard. A value that is approximately correct may only be obtained by a knowledge of local conditions, and the habits of the panner. The volume of a 20–2½-inch batêa, when level full, is about 262 cubic inches, or about 0.0056 cubic yard.

The standard gold pan is ordinarily made of sheet steel, but if obtainable, pans of stainless steel are preferable because they are resistant to rust. Ordinary steel pans must be carefully dried after using, and if they rust while in use, as sometimes happens, they must be scoured with sand before drying. An

ordinary sheet steel pan, in the hands of a slovenly worker, is soon ruined, but even stainless steel pans should be dried after using. Gold pans of standard size are also made of copper, for use in the amalgamation of fine-grained gold, but for general work these are less serviceable than steel pans. Another pan, called a riffle pan, is fluted along its side for about a third of its circumference. This construction may be helpful to the novice, but is undesirable for general panning. When it is desired mechanically to reject a part of the material to

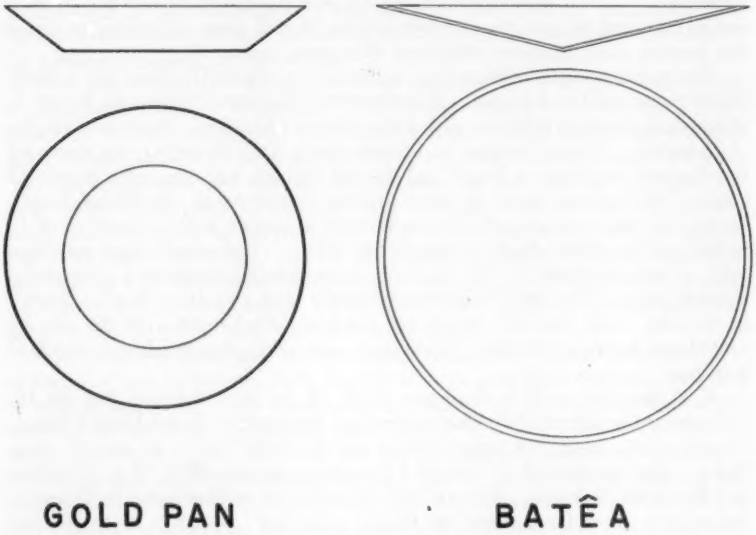

FIG. 1. A 16-inch standard gold pan and a 20-inch Brazilian batêa, both 2½ inches deep.

be panned, say the coarser fraction, a pan may be perforated to convert it to a sieve. This technique is more useful in panning sand and gravel than in panning decomposed bedrock, but in either case is hardly needed by a skilled panner.

Factors in Panning.—The concentration of gold, platinum metals, and other heavy minerals of value from fluvial and beach deposits by the use of the gold pan is too well known to merit description. This paper is concerned mainly with the application of the gold pan in sampling decomposed bedrock, residual and eluvial deposits derived therefrom, and hardrock that has been crushed and milled to a fine powder. Gold, platinum metals, and even the tungstates and cassiterite have higher densities than the accessory minerals derived from igneous and metamorphic rocks, and therefore their panning is simpler. A mediocre panner can recover nearly all the gold from a panful of gravel in a few minutes; but an expert panner will require from 5 to 10 times as long to re-

cover 80 to 90 percent of the accessory minerals in a sample of saprolite, and longer to get an equal recovery from a pan of powdered hardrock.

Hardrock breaks down under weathering to a soft material, commonly called saprolite in the southeastern States, that may be picked, shoveled, sacked, and panned. Owing to pore space produced by the alteration and partial solution of some of the rock-forming minerals, saprolite is less dense than the rock from which it is derived. The decrease in density, however, is inconstant, owing to the degree of alteration and removal in solution, the content of water, and other factors. An average value, however, has been obtained by repeated trials; and this is such that a standard gold pan, moderately heaped, will contain about 22 pounds of saprolite, or 10 kilograms. The latter is a useful figure in computing the tenors of accessory minerals, as these are weighed in grams. The error that accrues in the tenor of heavies, for a sample that is 2 pounds lighter or heavier than 10,000 grams, if the heavies have an average weight of 12 grams, will amount to only one significant figure in two digits, changing the tenor of 0.12 percent respectively to 0.13 or 0.11 percent. This difference is so small that it is more than offset by other variables that cannot be evaluated.

Peele (4), in speaking of the panning of gold placers, states that an experienced man can pan about 10 pans of average gravel per hour for 10 hours, or a pan every 6 minutes. A skilled panner will require from 20 to 30 minutes to recover the concentrates from a pan of saprolite, if a recovery of 80 to 90 percent is demanded. Usually, taking into account the time lost in going back and forth from the car to the panning site, and in refilling the pan with a new charge, the latter time is closer to an overall average. Peele also comments on the fact that panning is slow, back-breaking work. Certainly panning is no occupation for a gentleman geologist. The writer has stated to his coworkers that a day's work in panning saprolite should be 14 pans or 7 hours, whichever comes first. Some samples of saprolite, however, are very difficult to pan, if they contain clay that does not disintegrate in water, but coagulates instead into puttylike balls. Such lumps may be reduced to smaller size only by squeezing each individual piece between the fingers. The writer has spent an hour on a sample of this kind, without reducing the clay to pellets smaller than buckshot. Under such conditions, heavies are lost even after an hour of preliminary work.

Powdered bedrock requires more time to pan than weathered bedrock. All the unaltered feldspar is present, and must be removed by panning, whereas in weathered bedrock the feldspar is altered largely to clay, and floats off when the charge is kneaded, prior to panning. Moreover, unlike weathered bedrock, there is no quick shrinkage of powdered bedrock when placed in water. Therefore, the pan cannot be filled more than level full, as otherwise a part of the charge will overflow the lip of the pan with a consequent loss in heavies. More care must also be used in panning powdered bedrock, to keep the heavies back from the lip of the pan.

At least two pans are needed by every panner, and for some purposes three or four are required. Samples of 25 to 30 pounds are commonly taken for learning the nature and tenors of the accessory minerals, but if it is desired to

obtain a quantity of zircon or monazite sufficient for chemical analysis, samples of several hundred pounds may be needed. The writer panned 3,000 pounds of the Whiteside granite, from the Great Smoky Mountains of North Carolina, to obtain 2 grams of zircon. Therefore heavies will accrue from repeated pannings of a single sample, and these are most safely kept in another pan, covered by a small amount of water, as in this way they cannot be blown away. Under some circumstances, as later described, a large volume of concentrates needs to be repanned, to separate heavies from semiheavies; and in such an operation, one pan will be needed for the original concentrates, a second for the operation of repanning, a third as a container under the operating pan, and a fourth for the separated heavies.

The gold pan, in the hands of an experienced operator, is a versatile and efficient tool. Compare it, for example, with conventional concentrating devices that operate by the action of gravity. The gold pan is a portable field tool; the concentrating table, the Humphrey spiral, and the superpanner are laboratory or commercial equipment. The gold pan handles unclassified material from coarse gravel to clay; concentrating devices, on the other hand, require preclassification of all materials. A panner automatically controls the volume and speed of water entering and leaving his pan; but controls are needed for concentrating devices, both for the flow of water and the mineral feed. The gold pan, in the hands of a skilled operator, will save almost as high a percentage of heavies as the concentrating table. The gold pan, of course, will not separate minerals into separate fractions as the concentrating table or Humphrey spiral will do, but this can be accomplished to a practicable degree by the use of magnets. The writer has often been asked why he did not rig up some automatic device for use in the field, to obviate the great labor of panning. If and when portable equipment is designed that will give results equal to those obtainable with a gold pan, the writer will be the first customer.

Operation of Panning.—The panning of weathered bedrock, or of powdered hardrock, should be done in a shallow pool of water, in which a very slight current flows. The writer, after picking a suitable site for panning, ordinarily shovels out a circular basin, with a diameter of 2½ or 3 feet, and a depth of about 6 inches, alongside a small stream, and preferably on a gravel bar, such that a back eddy from the stream circulates the water very slowly around the pond. A moderately heaped pan of saprolite is then lowered to the bottom of the pond, and the charge is kneaded from the outside of the pan inward, so that no material escapes over the lip. This kneading loosens the clay, which then arises and is carried away by the current. Even if the panning is done in a pond where there is no current, the clay still moves outward from the pan. Kneading is continued until no further muddy water arises, whereupon, with the clay removed, the remaining part of the sample is ready to be panned.

The operation of panning for heavy minerals cannot be adequately described; it must be seen and practiced. With sufficient water to cover the charge, the pan is shaken vigorously with a lateral motion, which causes the heavies to migrate to the bottom, and the rock-forming minerals to rise to the top. Even large pieces of quartz or feldspar will thus work to the upper sur-

face of the charge. After a certain amount of this lateral motion, the panner will decide when enough of the lighter minerals have arisen; and in the later stage of this agitation, the pan is tipped gradually forward, so that when it is time for washing, the upper surface of the charge will be flush with the lip. The lighter top material is now washed off by a shallow sheet of water that is admitted to the pan more slowly than it is discharged. The flow of water is best adjusted to have a somewhat circulatory, as well as an inward and outward motion. With the charge properly disposed in the pan, as above described, no gully is cut at the lip, and therefore no heavies are lost. After the lighter and coarser material of one layer has been removed, a second is raised by lateral agitation, and similarly washed out of the pan. This process is continued until the sample is reduced to a volume suitable for cleaning. Care must be taken in the operation of washing, because large crystals of heavy minerals as well as the rock-forming minerals tend to rise by agitation. If this fact is not recognized, and controlled by proper panning, large crystals of heavies, such as the iron ores or monazite, may be washed over the lip and lost.

Cleaning of a sample of concentrates is necessary because very small crystals of any kind, regardless of their densities, tend to accumulate at the bottom of the pan. Thus a considerable volume of small crystals, or minutely divided fragments, of quartz may remain with the heavier concentrates; and garnet or epidote of a similar size is even harder to eliminate. Concentrates may be cleaned in three ways, and usually all three are employed. First is a special type of washing, employing a deft motion of the pan, by which the remaining crystals or mineral particles coarser than sand are caused to roll or walk outward, overriding the finer concentrates, and passing over the lip of the pan. All these coarser particles may not be so eliminated in one stage; and frequently the later cleaning is interrupted to complete this first stage. Second, with the concentrates held back from the lip, they are vigorously agitated in a small amount of water. This causes fine-grained quartz or similar minerals of low density to rise in suspension, so that by quick action the water containing these particles may be poured off. If some of the suspended particles sink before reaching the lip, the third operation is performed, which consists of wiping out this material with the thumb of one hand. Cleaning thus consists of washing, floating and wiping. Great patience is required in the later stages of floating and wiping, as few of the lighter minerals appear to be leaving the pan. But if one works in the sun, the light rays in the water will illuminate these minute particles, and will convince the skeptic that minerals are constantly being eliminated. The process of cleaning is stopped when quartz and other rock-forming minerals no longer appear to be an essential part of the heavies.

Heavy accessory minerals, such as the iron ores, zircon, and monazite, may be accompanied by semiheavy minerals, exemplified by garnet, epidote, or sillimanite, which may be present in large volume. Ordinary panning will not save all these semiheavies, and a decision must be made whether they are to be eliminated or saved. If they are not particularly desired in the concentrates, a large part, but not all of them, may be removed by the methods so far

described, in which case an estimate is made and recorded of the percentage that is lost. If they are to be saved, the washing is stopped at an early stage, while a great deal of quartz and other minerals of low density still remain in the pan. The heavies thus remain mixed with a large volume of lighter minerals, and in this form the various fractions may later be separated in the laboratory by the use of magnets and heavy solutions. But this is unsatisfactory to the field man, who wishes to know immediately the character and amounts of the heavies in his sample. The heavies can be separated from the semiheavies, saving both, only by a process of fractional panning, so named by the writer from analogy with fractional precipitation and fractional distillation. The large bulk of concentrates is closely panned from one pan to another, deliberately losing a part, even a large part, of the heavies, in order to obtain a sample that is practically free of semiheavies. The panned off material is then repanned, to obtain a second fraction of relatively pure heavies; and sometimes this process is repeated 10 or more times, to make a complete separation of heavies from semiheavies. This method is laborious and time consuming, but appears to be the only possible technique employing a gold pan alone.

Processing of Concentrates.—A sample of concentrates is washed or wiped from the gold pan onto a piece of white unlined rag paper of looseleaf notebook size, say 5 by 8 inches; and after pouring off any excess water is so folded that the concentrates cannot escape. The sample is then numbered and refolded in another sheet of some absorbent material, such as newspaper. Thus much of the moisture is absorbed from the time of panning until the samples are opened some hours later. At night, all samples are dried by spreading them, still in the first wrapper, on a small electric heater, equipped with a metal plate. The heating is so arranged that the paper will not char unduly. After drying, the sample is poured onto a clean sheet of rag paper, and if spread thin, will cool in a few minutes. All samples are stored in glass bottles, of which five sizes are carried, each having from one third to one half the volume of the next larger size. The smallest vial, which measures 19 by 50 mm., contains about 15 grams of a mineral with a specific gravity of 5. Labelling is done with gummed stickers, with descriptions in ink.

A field geologist needs to know the nature of the concentrates collected one day in order to plan his work for the following day. Therefore each sample is separated the same evening into four fractions, as follows: first, a magnetite fraction; second, a fraction containing ilmenite and other minerals of approximately the same magnetic susceptibility; third, a weakly magnetic fraction containing monazite and other weakly magnetic minerals; and fourth, a nonmagnetic fraction containing zircon, pyrite, and other nonmagnetic minerals. This separatory work is done with three alnico magnets, usually 3-inch, 4-inch, and 6-inch magnets. A portable electromagnet is also used in place of the 6-inch alnico magnet.

Monazite and xenotime, occurring respectively in the third and second fractions, are recognized by the use of a hand spectroscope. Monazite, owing to its content of neodymium, shows a broad absorption band in the yellow, and a narrow, less conspicuous, band in the green. Xenotime, if it contains both erbium and holmium, shows two narrow absorption bands in the green,

and none in the yellow. These absorptions may be recognized in sunlight, diffused daylight, or by the light of a Mazda lamp, but are most apparent in a spectroscope with an adjustable slit. A narrow slit gives the best definition, but in sunlight and daylight confusion may arise from the presence of Fraunhofer lines. The writer has found that these absorption bands are best defined by the light of a high powered condensed filament, focused through a lens onto the specimen. Such a light gives a bright continuous spectrum, in which Fraunhofer lines are absent.

The zircon of most granitic rocks, other than pegmatites, is fluorescent, and may therefore be recognized by ultraviolet light. The proportion of fluorescent zircon is estimated by comparing the nonmagnetic fraction of the concentrates with reference samples of zircon mixed with some non-fluorescent mineral, and by matching the degree of fluorescence. For this purpose, vials of fluorescent zircon mixed with rutile are used, in which the percentages of zircon range from 0.1 to 50.0 percent. If the zircon of the specimen is non-fluorescent, or only partly fluorescent, this technique will not work, but this condition is uncommon in ordinary granitic rocks. The method may also be somewhat vitiated by the fact that some zircon is weakly magnetic, owing to the presence of ferromagnetic inclusions. This defect may be remedied by examining the concentrates of fractions two and three in ultraviolet light.

The suite of accessory minerals occurring in igneous and metamorphic rocks is not large, so that a hand lens serves to identify and to estimate approximately the tenors of the principal other minerals, besides magnetite, ilmenite, monazite, xenotime, and zircon. Final determinations are made in the laboratory, at the end of the field season.

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EXTRACTION OF URANIUM FROM AQUEOUS SOLUTION BY COAL AND SOME OTHER MATERIALS[1]

GEORGE W. MOORE

ABSTRACT

Uranium in nature is commonly associated with carbonaceous material. Laboratory studies were therefore conducted to determine the relative ability of various types of carbonaceous material and some other substances to remove uranium from solution. The results of these experiments indicate that the low-rank coals are more effective in extracting uranium than any of the other materials used. A chemical determination shows that nearly 100 percent of the available uranium in solution is removed by subbituminous coal. The uranium is apparently retained in the coal by an irreversible process. The notable affinity of uranium for coalified plant remains suggests that some uranium deposits may have been formed over a long period of time by the extraction of uranium from dilute groundwater solutions. A possible application of the results of this work may be the extraction of uranium by coal from natural water or from waste solutions from uranium-processing industrial plants.

INTRODUCTION

THE association of uranium with carbonaceous material in nature has been recognized for many years. In 1875 Berthoud (1) [2] reported the occurrence of uranium minerals with coal in the Leyden area, Jefferson County, Colo., and in 1905 Boutwell (2) noted the association between uranium and fossil wood on the Colorado Plateau. Recent work has shown that uranium occurs with many types of carbonaceous material including marine black shale (13), carbonized plant remains (7), asphaltite (5), crude oil (16), and coal (15).

A detailed study of uranium-bearing lignite in South Dakota led Denson, Bachman, and Zeller (6) to propose that the uranium in these deposits was introduced by cold ground-water solutions subsequent to coalification. This hypothesis has been summarized by Love (12). A requirement of this hypothesis is that coalified plant remains and uranium have a strong chemical affinity for each other and that carbonaceous material has a capacity for extracting uranium from dilute solutions. Experiments were conducted in order to establish the relative ability of coal to remove uranium from solution under laboratory conditions. Other materials, some of which are commonly associated with uranium in nature, were also tested.

[1] Publication authorized by the Director, U. S. Geological Survey. This report concerns work done on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission and is published with the permission of the Commission.

[2] Numbers in parentheses refer to References at end of paper.

ACKNOWLEDGMENTS

T. S. Lovering participated actively in the early parts of the study and made many suggestions throughout the course of the work. The analytical work was done by the U. S. Geological Survey, by Wayne Mountjoy, J. P. Schuch, and W. W. Niles, under the direction of L. F. Rader, who also suggested methods of procedure and kindly read the manuscript. Samples were obtained from F. C. Bennett of the Colorado Fuel and Iron Corporation, J. B. Goodman of the U. S. Bureau of Mines, and J. W. Adams, J. R. Donnell, Harold Masursky, and H. D. Zeller of the U. S. Geological Survey. This work was done on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission.

DESCRIPTION OF EXPERIMENTS

A solution of uranyl sulfate containing 1.0000 g of uranium was prepared by dissolving 1.1793 g of powdered uranium oxide [3] in a mixture of concentrated nitric and sulfuric acids. This solution was evaporated to dryness and fumed to remove the nitrate ion, and the residue was then dissolved in 1 liter of 0.01 normal sulfuric acid to provide a *p*H of 2. The solution of UO_2SO_4 thus prepared (11) contained 1,000 ppm uranium. For purposes of the experiments the solution was further diluted with water until it contained about 200 ppm uranium at a *p*H of 2.45.[4] The low *p*H value was selected to prevent the possible formation of insoluble hydrates (10).

In an initial experiment, coal from the Centennial mine, Boulder County, Colo., was ground and screened until it was composed of grains between 40 and 80 mesh (0.42–0.177 mm). This granular coal was placed in an apparatus similar to that described by Garrels *et al.* (9), which provides a continuous circulation of the solution. A solution (350 ml) containing 196 ppm of uranium was placed in this apparatus with 28 g of coal and the solution circulated for 12 days. The results of this experiment are given in Table 1.

TABLE 1

RESULTS OF EXPERIMENT ON THE PRECIPITATION OF URANIUM BY SUBBITUMINOUS *B* COAL FROM THE CENTENNIAL MINE, BOULDER COUNTY, COLORADO

	Before experiment	After experiment
Uranium in the coal (percent)	0.00016	0.21
Uranium in solution (parts per million)	196	0.48
$(SO_4)^{=}$ (parts per million)	342	218
*p*H	2.45	6.03

From the figures in Table 1 it can be seen that the subbituminous coal removed almost 100 percent of the uranium in the solution. In order to test whether the reaction between uranium and subbituminous coal is reversible, the material from the experiment was washed with distilled water, decanted 6 times, and a sample taken for analysis; then it was washed 6 more times and another sample taken. The analyses showed that after both 6 and 12 washings no uranium had been removed. These results suggest that the

[3] Mallinckrodt standard sample MS-ST, 99.95 percent U_3O_8.
[4] *p*H values listed in this paper were determined with a glass electrode.

TABLE 2

RESULTS OF EXPERIMENT IN WHICH 16 MATERIALS WERE IMMERSED IN A SOLUTION OF URANYL SULFATE FOR 19 DAYS

Sample	Uranium content of sample (percent)		Composition of solution after experiment		
	Before experiment	After experiment	Uranium (parts per million)[1]	pH[2]	$SO_4^{=}$ (parts per million)[3]
Wood					
White pine	0.0000	0.14	120	2.80	384
Peat					
Chisholm, Minn.	0.0005	0.21	4.0	4.28	268
Lignite					
Sandow mine, Tex.	0.0002	0.17	4.0	6.56	864
Lignite					
Slim Buttes, S. Dak.	0.0003	0.19	2.0	3.97	894
Subbituminous C coal					
Suntrana mine, Alaska	0.0001	0.21	0.24	4.90	321
Bituminous coal (HVC)					
Kebler mine, Colo.	0.0001	0.012	166	7.57	410
Anthracite					
Crested Butte, Colo.	0.0001	0.024	132	5.10	348
Graphite					
Commercial	0.0000	0.044	144	7.74	400
Charcoal					
Commerical	0.0000	0.022	137	7.90	349
Phosphate rock					
Cokeville, Wyo.	0.028	0.11	74	7.28	711
Bentonite					
Upton, Wyo.	0.0030	0.099	145	7.50[4]	—
Oil shale					
Rio Blanca, Colo.	0.0037	0.031	158	7.50	410
Canneloid coal					
Wamsutter, Wyo.	0.0002	0.16	39	1.63	4750
Calcite					
Iceberg mine, N. Mex.	—	0.002	168	7.63	—
Gilsonite					
Middle Park, Colo.	0.0013	0.004	180	2.41	410
Silica flour					
Commercial	0.0000	0.002	200	2.46	350

[1] Uranium in original solution: 200 ppm.
[2] pH of original solution: 2.45.
[3] Concentration of $SO_4^{=}$ in original solution: 342 ppm.
[4] Determination probably inaccurate as sample contained colloidal bentonite, which could not be separated without changing the pH.

uranium is held irreversibly, at least in respect to distilled water, and perhaps in a manner similar to the occurrence of uranium in marine black shale (14). Tolmachev, on the other hand, has shown that uranium is adsorbed by charcoal in accordance with Freundlich's law and that the quantity of uranium extracted is proportional to the amount of uranium in the solution (14). He further demonstrated that the uranium could be removed from the uranium-bearing charcoal by flushing with distilled water. Thus, it appears that the mechanism whereby uranium is extracted from solution by charcoal is different from that in which it is removed by coal and black shale. A more detailed discussion of the factors influencing extraction is given below.

A second group of similar experiments was conducted using many different materials and employing a more simple apparatus. The samples included all the major ranks of coal and associated carbonaceous materials, as well as clay, phosphate rock, and additional substances considered as potential extracting agents of uranium from solution.

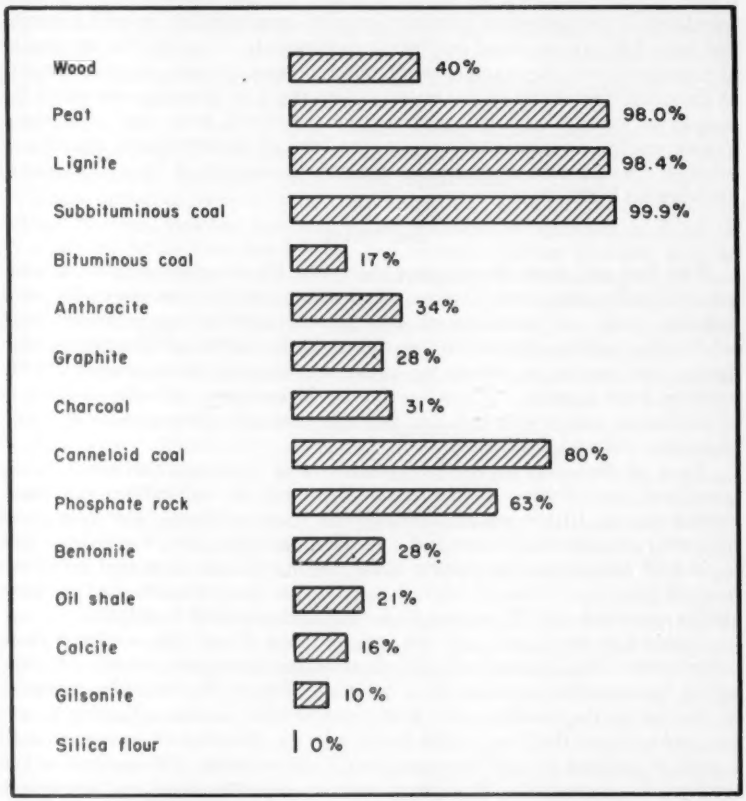

FIG. 1. Percent uranium extracted by coal and other materials from uranyl sulfate solutions containing 200 parts per million uranium

Each sample of material was ground until it would pass through an 80 mesh screen (0.177 mm). Then, 20.0 g of each sample was placed in a 500 ml bottle with 250 ml of uranyl sulfate solution at a *p*H of 2.45 and a uranium content of 200 ppm. The contents of each bottle were shaken thoroughly once daily for 19 consecutive days. At the end of this period, all the solutions were centrifuged at 1450 rpm for 15 minutes. Bentonite and lignite

from South Dakota were centrifuged at 2300 rpm because these solutions failed to clear at the lower speed. Even after this treatment the solution containing the bentonite remained cloudy.

Samples of the solid material were analyzed for uranium and the solutions were analyzed for uranium and sulfate ion, and the *p*H ascertained. The results of these analyses are shown in Table 2. The results have also been calculated to the percent of uranium removed from solution by each material, and these data are presented graphically in Figure 1. It is felt that the change of concentration of the uranium in solution represents a more accurate measure of the extracting ability of the material than the final uranium content of the sample, as several materials—particularly the wood, peat, and bentonite—formed spongy or gelatinous masses that held an indeterminate quantity of solution. As a result, the values for the uranium content of these samples are probably too high.

DISCUSSION

The first and most obvious fact shown by these experiments is that the low-rank coals were more effective in extracting uranium than any of the other materials used. A maximum of 99.9 percent uranium was removed from solution by subbituminous coal; phosphate rock follows subbituminous coal, lignite, and peat as an extracting agent, for it removed 63 percent of the uranium from solution. These results are in harmony with the association of uranium in nature with coal, coalified logs, and carbonaceous shale and with phosphate rock and fossil bones.

Most of the other materials extracted some uranium, but none can be considered as effective as the coal. Gilsonite, an asphaltlike substance, extracted only 10 percent of the uranium from solution. The adsorptive properties of bentonite for uranium have been attributed by Frederickson (8) to the high base-exchange capacity of the montmorillonite clays that constitute most of this rock. It is of interest to note that the bentonite used in these studies extracted only 28 percent of the uranium available in solution.

Concerning wood, peat, and the various ranks of coal, the results of these experiments (Fig. 1) indicate that these materials are not equally effective agents for removing uranium from solution. Wood, for example, extracted 40 percent of the uranium, and peat extracted 98 percent. Passing to the low ranks of coal there is a slight increase in the efficiency of extraction until a peak is reached at subbituminous coal, where almost 100 percent of the uranium was extracted. Bituminous coal, on the other hand, extracted only 17 percent, while anthracite and graphite removed only 30 and 28 percent respectively.

These results are of a preliminary nature, based in most cases on a single sample for each rank of coal, so additional studies may alter the pattern that seems indicated. If these results are accepted as approximating those that would be obtained regardless of the number of samples used, the chief factors influencing the extraction of uranium by coal may be considered. These are: Surface adsorption, ion exchange, chemical reduction, change in *p*H, and the formation of metalo-organic compounds.

The fact that the uranium is held irreversibly by the coal suggests that surface adsorption phenomena are not important in determining the affinity for uranium. Also, Breger and Deul (3) have shown by base-exchange studies that the uranium in coal is not held to any appreciable extent by ion exchange.

Coal is generally regarded as a good reducing agent, but the results of these experiments are inconclusive as to the role chemical reduction may play in the extraction of uranium. Bituminous coal, anthracite, and charcoal are relatively poor extracting agents for uranium, but there is no chemical reason known to the writer for regarding these as less effective reducing agents in general than the low ranks of coal. Until further studies are made, it is suggested that chemical reduction is not an important factor in the precipitation of uranium under the conditions of these experiments.

There also appears to be little relation between the ability of materials to extract uranium and the final pH of the solution as indicated in Table 2. Precipitation as an insoluble hydrate in a neutral solution does not seem to have been an important factor, since anthracite, a poor extracting agent, had a more nearly neutral final solution than, for example, subbituminous coal, a good extracting agent. Similarly the concentration of sulfate ion in the final solution seems to have little relation to the amount of uranium extracted.

Since the uranium is apparently held irreversibly in the coal, it is possible that the uranium is precipitated as a metalo-organic compound as suggested by Breger and Deul (3) on the basis of experimental work on natural uranium-bearing lignite. If this is the mechanism, the organic compound that combines with the uranium may reach its maximum development in subbituminous coal. Further metamorphism of subbituminous coal to bituminous coal could destroy the organic compound important in extracting uranium. Breger and Whitehead (4) have shown by thermographic studies that a relatively strong exothermic peak occurs at about 650°C with subbituminous *A* and high volatile *C* bituminous coals. This peak is not present in subbituminous *C* coal or in lignite. It is possible that the same conditions that give rise to these thermographic characteristics may also reflect changes that make the higher ranks of coal less effective extracting agents for uranium.

The anthracite and graphite used are somewhat better extracting agents than the bituminous coal. It is possible that further metamorphism of the bituminous coal to anthracite and graphite could create the ability for removal of the uranium in a different manner—perhaps by ionic adsorption between the graphitic layers. This would be similar to the mechanism whereby charcoal is thought to adsorb uranium; and if this is the case, the uranium would not be *fixed,* as the reaction is reversible for charcoal. The possibility that the uranium is held in this manner by anthracite and graphite was not tested.

CONCLUSIONS

Of the materials studied, peat, lignite, and subbituminous coal are the most effective agents for the removal of uranium from solution. Phosphate rock may be considered as a fair extracting agent under the conditions of these

experiments. It is suggested that the common association between uranium and carbonaceous material in nature may result from the ability of these substances to remove uranium from natural solutions by the formation of metalo-organic compounds.

A possible application of the results of this work may be the commercial extraction of uranium from solution by coal and other carbonaceous materials. Subbituminous coal, lignite, or peat might be employed to concentrate uranium either from natural water containing small quantities of uranium or from waste solutions from uranium-processing industrial plants.

U. S. GEOLOGICAL SURVEY,
DENVER, COLO.,
Feb. 20, 1954

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DISCUSSION

COMMENTS ON THE IRON DEPOSITS OF THE CONGONHAS DISTRICT, MINAS GERAIS, BRAZIL[1]

Sir: The paper entitled "The Iron Deposits of the Congonhas District, Minas Gerais, Brazil," by Philip W. Guild, published in ECONOMIC GEOLOGY, Vol. 48, No. 8, December, 1953, is stated to be in the nature of a progress report. This paper presents an hypothesis of the genesis of oxide-facies iron formation evolved by Guild, and restates, with some additional evidence, a theory of origin for the Minas Gerais iron ore deposits that has been in the process of evolution for a number of years and that was discussed at some length in another recent paper.[2] Guild's paper also presents regional field information as known up to 1951, as well as much valuable petrographic information obtained by him since then.

Since 1951 the field mapping being carried on by the U. S. Geological Survey and the Departamento Nacional da Produção Mineral in the central Minas Gerais iron ore area has disclosed much new information about the regional geology of that area, some of which has an important bearing on the interpretations and hypotheses developed by Guild. As it will be some time before the results of these later studies can be published in formal reports, comment on certain aspects of Guild's paper in the light of this more recent information may be of interest to students of iron geology.

Specific points that seem to deserve comment at this time are: a) evidence concerning possible volcanic influence on the genesis of the oxide-facies iron formation; b) evidence relating to structural control of the ore bodies; and c) evidence as to the type of iron formation most susceptible to replacement by hematite.

At the time Guild finished his field work the party mapping in the ferriferous area of Minas Gerais was not aware of the presence of a profound and extensive angular unconformity separating the Minas series, which includes the iron ore deposits, from an older group of rocks that seems to be in part of volcanic origin. In 1950 O. Barbosa[3] suggested the presence of such an unconformity, but it was not until 1953 that field evidence demonstrating

[1] Publication authorized by the Director, U. S. Geological Survey.

[2] Dorr, J. V. N., II, Guild, P. W., and Barbosa, A. L. M., 1952, Origin of the Brazilian iron ores: XIX Congrès Géologique International, Alger, Symposium sur les Gisements de Fer, p. 286–297.

[3] Verbal communication on the "Barbacena series" given before to IV Geological Congress of the Sociedade Brasileira de Geologia at Ouro Preto, 1950.

its actual existence and nature in the iron region was documented.[4] This unconformity has now been mapped in nine quadrangles to the north of the Congonhas district and will undoubtedly be found in others as mapping progresses.

It now seems likely that Guild, like many other geologists, may have included pre-Minas rocks in his upper and lower groups of the Minas series. Thus the cores of rocks with volcanic affinities cited in his description of the upper Minas rocks are from pre-Minas rocks. Furthermore, the "green schists" described by Guild may well be older than he supposed, for the pre-Minas rocks north of the Congonhas district have a similar lithology, including many thin lenses of lean itabirite, and it seems more reasonable to correlate the "green schists" with these rocks than with the entirely dissimilar Minas series. Such an interpretation negates the principal evidence indicating volcanic activity during Minas time that, according to Guild, could have influenced the deposition of the iron formation.

Guild reports the presence of rocks with volcanic affinities in the upper portion of the dolomite zone of the middle group of the Minas Series in the Congonhas district, and similar rocks have been found in equivalent stratigraphic positions in other parts of the region. This zone is stratigraphically much higher than the bulk of the iron formation. However, no rocks of volcanic origin have yet been found within or closely associated with the bulk thickness of the oxide-facies iron formation or in the underlying rocks of the lower group of the Minas series. The upper group of the Minas series probably includes some rocks of volcanic origin, although this probability is yet to be confirmed by additional stratigraphic and petrographic work.

Evidence for volcanic activity that might have had an influence on the sedimentary environment and development of the oxide-facies iron formation thus seems to be entirely lacking in the region.

With respect to the structural control of ore, Guild emphasizes brecciation caused by pre-ore thrust faulting and concludes that this structure afforded channelways and loci for replacement in the Congonhas district. He also suggests that hypothetical thrust faults in the Serra do Curral are responsible for localization of ore in that range.

The ore bodies in the Serra do Curral are on the lower limb of an overturned anticline, an unknown distance from the crest. There seems to be no reason to postulate major thrust faulting within the range, for the stratigraphic sequence, although inverted, is not disturbed.

In other parts of the region as well, the brecciation due to thrust faulting does not appear to be genetically important because most deposits are localized either on the flanks or axes of folds or by abrupt steepening of linear structure. Perhaps the best known example is the Itabira district, where the ores are clearly controlled by tight, intricate folding (see maps by Sanders[5]). The bodies are localized in three synclines, two of which are overturned and one

[4] Rynearson, G. A., Pomerene, J. B., and Dorr, J. V. N., II, 1954, Contacto basal da serie de Minas na parte ocidental do quadrilatero ferrifero, Minas Gerais, Brasil; Avulso 34, Divisao de Geologia e Mineralogia, DNPM, Rio de Janeiro.

[5] Sanders, B. H., 1933, Iron ore at Itabira (Minas Gerais), Brazil: Inst. Min. & Met. Bull. 346, London, p. 1–23.

of which is isoclinal. No pre-ore faulting has been recognized and post-ore faulting is minor.

Outside the Congonhas area, although thrust faulting has been mapped, in no case can it be demonstrated to be related to ore formation. Cross faulting, mostly normal, is abundant but also unrelated to ore.

Extreme plasticity under stress is an outstanding characteristic of oxide-facies iron formation in many parts of the world. In Minas Gerais, flowage folding and the most intimate crumpling are commonplace not only in the iron formation but also in the pure hematite that replaced it and preserved the pre-existing structures. That the intimate deformation is tectonic rather than the so-called preconsolidation slump of other iron districts is proved by the regional parallelism of fold axes. The pre-ore plasticity of the iron formation generally resulted in deformation by folding rather than faulting under orogenic stress. Complex folds, ranging in amplitude from millimeters to tens of kilometers, are ubiquitous throughout the region. The pure ores, on the other hand, and, to a lesser extent, the post-metamorphic iron formation, are brittle and in many places have been thoroughly brecciated by post-ore faulting.

Extreme folding of the iron formation can and does produce macrobrecciation, as can be seen from Guild's Figures 14 and 15. Microbrecciation from this cause should be even more widespread. These types of brecciation are common and undoubtedly facilitated the movement and attack of replacing solutions. Although both types have been healed by either early or late hematite, it does not seem likely that such structures effected much control over localization of the ore bodies, since the structures can be found not only in the ore but also in the adjacent unreplaced iron formation.

Thus it would appear that brecciation due to faulting would be a special rather than general controlling factor in the localization of ore bodies and may be of importance only in the Congonhas district, perhaps because, according to Guild, only that district suffered pre-ore thrust faulting of a type that produced brecciation in zones favorable for replacement by iron-bearing solutions.

An alternative hypothesis attempting to relate ore genesis to the types of structural control most widely observed in the region was presented in the cited paper for the symposium on iron of the XIX International Geological Congress.

Guild's paper attaches considerable importance to the role the carbonate content of the iron formation had in the formation of ore bodies. He states that beds with a high carbonate content probably were more susceptible to replacement and that their replacement gives rise to more massive ores.

As more and more is learned about the stratigraphy of the iron formation in Minas Gerais, it becomes more apparent that the lower, siliceous part contains but little carbonate, except possibly in the Ouro Preto-Marianna area, which contains no significant bodies of pure hematite. The upper part of the iron formation, however, contains many lenses of dolomite as well as material that might be referred to as dolomitic itabirite or dolomitic chert but which is so weathered in most places that any original carbonate it might have contained is rarely seen.

The Congonhas district may be an exception, but elsewhere in the region the major ore bodies appear to have their greatest and generally exclusive development in the lower, siliceous, relatively carbonate-free parts of the iron formation. Moreover, large portions of these bodies are composed of massive, blocky ore. Thus the familiar situation seems to be reversed, for it appears that the more siliceous rocks were the more susceptible to metasomatic action.

Early papers resulting from a continuing study of a region by several geologists may well contain some statements and interpretations that cannot be reconciled with facts disclosed at later stages of the study. The principal intent of this commentary is to indicate to readers of ECONOMIC GEOLOGY wherein the context of Guild's paper may be subject to revision or modification on the basis of new field evidence. An attempt has also been made to point out that certain features of the ore deposits of the Congonhas district, as they have been described by Guild, are not necessarily representative of the deposits in other parts of the region. It is expected that forthcoming reports will describe these other deposits in enough detail and that sufficient general information will be accumulated to permit the preparation of a comprehensive report on the iron ores of the region as a whole.

JOHN VAN N. DORR II

BELO HORIZONTE, BRAZIL,
May 4, 1954

REVIEWS

Crystal Data, a classification of substances by space groups and their identification from cell dimensions. By J. D. H. DONNAY and WERNER NOWACKI with the collaboration of GABRIELLE DONNAY. Geological Society of America, Memoir 60, 1954. Pp. xii + 719; figs. 4. Price, $5.00.

Part I (133 pp.) is W. Nowacki's *Classification of crystalline substances by space groups,* revised to mid-1948. The statistical conclusions are little changed since the edition of 1942: ten of the 230 space groups contain 46 percent of the known crystals. The less symmetrical groups are now being found somewhat more frequently as techniques for determining crystal structures improve. Various statistical data are tabulated.

Part II (460 pp.) comprises the Donnays' determinative tables for the identification of crystalline substances from cell dimensions. This table lists all substances for which the axial lengths and angles are known, arranging them first by systems (properly treating rhombohedral lattices as centered hexagonal), and arranging crystals within the systems according to increasing ratios a/b in the trimetric and c/a in the dimetric systems, and according to increasing a in the isometric system. A useful appendix of X-ray criteria for determining space groups concludes this section. The volume contains two 60-page indexes, one for formulas and one for names. The book will be most useful in laboratories where single-crystal diffraction work is in progress. Theoreticians will find valuable empirical data in Part I. References are cited throughout each of the main tables.

HORACE WINCHELL

YALE UNIVERSITY,
NEW HAVEN, CONN.,
May 5, 1954

Edelsteine und Perlen. By K SCHLOSSMACHER. Pp. viii + 280; figs. 103; tbls. 3. Verlag E. Schweizerbart, Stuttgart, 1954. Price, DM 25.—.

The verbose vagaries of the German language result in the fact that this book lies somewhere in the broad borderland between an elementary text and a popular account. Although it fills neither of these purposes satisfactorily the author has accomplished the concentration of much interesting information. Professor Schlossmacher admits that it is a compromise; that he intended it neither for pure science nor for popular consumption. One is therefore forced to conclude, by the author's own words, that its appeal must necessarily be small.

The book is divided into three parts: general information, including the properties of precious stones and the methods of examining them; specific descriptions of the various gemstones with reference to their properties, occurrence, origin, imitations, well-known specimens, trade and prices; and applied lapidary such as the cutting, polishing and engraving of stones. Many of the concepts explained in the first part lead to oversimplifications which are not warranted. For example, the reversion to the archaic chemical nomenclature of the silicates is not tenable in the light of modern structural knowledge; indeed, the older usage was abandoned in

America more than a generation ago. Moreover, the reference to the spinels as aluminates is erroneous if the isodesmic bonding of this group is considered. More space (33 pp.) is devoted to a description of the diamond than to any other mineral group. The economics of the diamond industry, including a discussion of the activities of the syndicate, is reviewed for the period 1937–1951 and valuation data are recent and timely; most of them are less than one year old. Some information is used in the second part which is not previously explained in the text. Only 20 pages are devoted to pearls and this does not include any information on economics and trade.

The book has several other unfortunate shortcomings besides the fallacious ideas resulting from overgeneralization (a case in point is the discussion of the origin of rocks). There are occasional misstatements of fact (labradorite is incorrectly included in the monoclinic system; moldavite is reported from Australia [australite, Darwin glass] and from the East Indies [billitonite]) and typographical errors. There is no bibliography and no reference to the literature of geology (it seems regrettable that the classic work of Ball, 1931, is overlooked). The reproduction of photographs leaves something to be desired and the figures are erratic; many of them are not credited to their original source.

It is with a sense of sincere regret that I must conclude that this book does not measure up to the high standards and usefulness we have come to expect from this publisher. Nevertheless, it is a handsome volume in physical appearance.

KURT SERVOS

YALE UNIVERSITY,
NEW HAVEN, CONNECTICUT,
May 28, 1954

Mountain Building. By REIN W. VAN BEMMELEN. Pp. 189; figs. 51. Martinus Nijhoff, The Hague, 1954. Price, 12.50 guilders (appr. $3.50).

Mountain building is always of interest to geologists and this book from the pen of a distinguished investigator and author is another noteworthy contribution to this subject. It is based primarily upon the author's careful studies of Indonesia, which is the region of the world's most active crustal deformations. Here are the many phenomena associated with mountain building—great downwarped zones, gravity anomalies, intrusive igneous rocks, volcanism, and seismicity. Some picture of these phenomena has already been given in the author's comprehensive study, *The Geology of Indonesia.*

In this book the author treats of the subject in two parts. Part I, The Principles of Mountain Building, deals with compression, extension, continual drift or growth, energy and the basic principles of the author's "undation theory," i.e., the geochemical concept of crustal evolution, and the bicausality concept of mountain building.

Part II is entitled, "The Orogenic Evolution of the Earth's Crust in Indonesia." Separate chapters cover stratigraphy, volcanism, tectonics, geophysics, and geological evolution. This latter part covers the evolution of mountain building and associated geological phenomena. The Indonesian belt, as the author points out, shows mountain building in progress at the present time, and the author adduces evidence that similar mountain building has proceeded in pulsations and laterally shifting placement during the last 200 million years.

The broad scope of this work with the author's interrelation of causes and processes in mountain building will make this a book of reference for all structural geologists.

The Coalfields of Great Britain. Edited by SIR ARTHUR TRUEMAN. Pp. xi + 396; pls. 7; figs. 106; tbls. 5. Edward Arnold, Ltd., London; St. Martin's Press, Inc., New York, 1954. Price 63 s.; $15.00.

"The present work is intended to supply mining engineers and students, particularly of mining and of geology, with a balanced account of the geology of coal and of the structure and resources of the coalfields of Great Britain." This is one of the rare cases in which the author's declaration of purpose did not outweigh his achievement. Sir Arthur Trueman, as editor and author of five of the sixteen chapters, has more than amply accomplished his difficult task. He has presented a well organized, serious and much needed volume on the geology of British coal.

The first five chapters, written by Sir Arthur, discuss coal in its general geologic aspects, the subjects being Coal as a Rock; The Rocks of the Coal Measures; Geological Structures; Fossils of the Coal Measures and Their Use, and The Origin of the British Coalfields. The remaining eleven chapters are each devoted to specific coal fields in England, giving a thorough analysis of the structure of each, with a list of references at the end of each chapter, and are written by a number of prominent investigators.

The book as a whole is highly readable, well illustrated and very concentrated so that the professional or the advanced student need waste no time thumbing through elementary information. This book is completely up to date in all its data, and until the next such work is published, some years hence, it should be of invaluable use to the audience for which it was intended.

B. A. BROMBERT

NEW HAVEN, CONN.,
May 19, 1954

Geography of North America. By GEORGE J. MILLER, ALMON E. PARKINS and BERT HUDGINS. Third Edition. Pp. xi + 664; figs. 290; tbls. 25. John Wiley & Sons, Inc., New York, 1954. Price, $7.50.

This third edition, like its predecessor, describes man's reaction to his natural environment. The central theme is man's occupancy of the continent and his utilization of the natural resources available to him. This brings up what are the natural resources, how he has used them and what are still available to him.

The structure of the book is simple. There is a Part I, The Continent and Man (32 pp.); Part II, The United States and Alaska (452 pp.); Part III, Canada (108 pp.); Part IV, Mexico and Middle America (64 pp.). Each of the Parts is subdivided into geographic units under which are discussed climate, agriculture, manufacturing, mining, and other industries. There are many graphs, charts, maps, illustrations and numerous references.

The material on the United States has largely been rewritten and is fairly well up to date. The geologist, however, might perhaps wonder about "Pure metallic copper" (p. 259), or the Arizona Copper Co., having a large smelter (long defunct) at Clifton near Morenc*ia*, and that the chief copper districts of Arizona are "Bisbee, Morenc*ia*, Metcalf, and Globe-Miami districts." This statement would have been correct 40 years ago—but long ago old Morenci and Clifton almost ceased to exist; Jerome is now a ghost town, and Globe is largely gone. Since 1910 the large copper mines of Ray, Ajo and new Morenci have come into existence. One would think that Leadville, Colo., is still an important mining district. Much of the parts on mining and mineral resources is very vague, out of date or erroneous. The material on agriculture appears to be more up to date.

Geochemistry. By the late V. M. GOLDSCHMIDT, edited by ALEX MUIR. Pp. 730; tbls. 96. Oxford at the Clarendon Press, London, 1954. Price, $11.04.

This book was in preparation by the author for many years. Part of it was written in Sweden during the occupation of Norway. Other parts were written while the author was in hospitals and nursing homes in Britain. Little was written after his return to Oslo in 1946. Part II, dealing with the Geochemistry of the Elements, was nearly completed before the death of the author, but the bulk of Part I, dealing with the principles, was never begun. This, the editor assembled from Goldschmidt's notes, earlier articles, and other translations.

Part I, 6 chapters, deals with the scope and development of geochemistry, distribution of the elements during the evolution of the earth, evolution of magmatic rocks, quantitative treatment of geochemical processes, chemical composition of the cosmos and of its separate mass concentrations, and principles of crystal chemistry in relation to geochemistry.

Part II, Geochemistry of the Elements, of 600 pages, treats of the groups and subgroups of the elements according to the periodic chart. Each element is followed through its distribution in the crust, in minerals, in soils, in mineral deposits and in sediments. Its crystal chemistry is given. This part embodies most of Goldschmidt's work at Oslo and Göttingen.

The book brings together a great mass of data on geochemistry, some of which is not up to date. The part on crystal chemistry is a summary of the development of the subject with which Goldschmidt's name will always be associated. Had he lived, Part I, and particularly the crystal chemistry, would have been brought more up to date.

The editor is to be congratulated for bringing the subject matter together in one book—a book that is bound to be a general reference work, even though it does not contain some of the later information. Had it not been preceded recently by Rankama and Sahama's *Geochemistry,* and Mason's *Principles of Geochemistry,* it would stand as the leading work on the subject.

BOOKS RECEIVED

FRANK G. LESURE

U. S. Geological Survey—Washington, D. C., 1954.

Prof. Paper 231. Physiography and Glacial Geology of Western Montana and Adjacent Areas. W. C. ALDEN. Pp. 200; pls. 5; figs. 43. *Study of glacial features in intermediate valleys and drainage area of upper Missouri and Columbia Rivers.*

Prof. Paper 254-B. Nonmarine Mollusks of Late Cretaceous Age from Wyoming, Utah and Colorado. TENG-CHIEN YEN. Pp. 45–66; pls. 3. Price, 60 cts.

Prof. Paper 255. Pegmatite Investigations 1942–45, New England. EUGENE N. CAMERON and others. Pp. 352; pls. 48; figs. 139. *Results of detailed mapping and study of more than 300 pegmatites. Description of 180 mines and prospects.*

Water-Supply Paper 1192. Water Levels and Artesian Pressures in Observation Wells in the United States in 1951. Pt. 2. Southeastern States. Pp. 229; figs. 36. Price, $1.00.

TEI-390. Geologic Investigations of Radioactive Deposits. Pp. 281; figs. 47; tbls. 13. *Many short papers on progress in studies of uranium in sandstone-type deposits, in veins, igneous rocks, carbonaceous rocks and phosphates.*

U. S. Atomic Energy Commission—Oak Ridge, Tennessee, 1954.

RME-3072. Fracture Studies in the Lucero Uplift, New Mexico. ROBERT W. DUSCHATKO. Pp. 49; pls. 10.

RME-4019. Investigation of Subsurface Isorad Methods, Temple Mountain, San Rafael District, Utah. Pp. 34; pls. 14; figs. 6.

Report of Sedimentation Survey, Great Salt Plains Reservoir, Salt Fork of Arkansas River, Oklahoma. Arkansas River Basin. Pp. 16; pls. 24; tbls. 8. Corps of Engineers, U. S. Army, Tulsa, Oklahoma. *Report covers period 1941–1949.*

Geological Abstracts, Vol. II, No. 1, March, 1954. Pp. 54. Geological Society of America, New York. *Second volume with a new and much more convenient format. Abstracts taken from copy contributed by editors of common geologic journals in America. It is hoped that future abstracts in these journals will become more informative.*

Minerals and Metals of Increasing Interest. Rare and Radioactive Minerals. RICHARD T. MOORE. Pp. 40. Arizona Bureau of Mines Min. Tech. Ser. No. 47, Bull. 163, Tucson, 1953. Price, 30 cts. *General features of the metals, mineral occurrences, price and possible buyers.*

Mineral Resource Research and Activities of the State Geological Survey, 1952–53. M. M. LEIGHTON. Pp. 54. Illinois State Geological Survey, Urbana, 1954.

State Geological Survey of Kansas—Lawrence, 1954.

Bull. 104. Oil and Gas in Eastern Kansas. JOHN MARK JEWETT. Pp. 397; pl. 1; figs. 59; tbls. 73. *Includes brief description of surface and subsurface geology and oil and gas developments in 43 counties.*

Bull. 106. Geology and Ground-Water Resources of Marshall County, Kansas. KENNETH L. WALTERS. Pp. 116; pls. 7; figs. 7; tbls. 11.

Bull. 109, Pt. 3. Significant New Exposures of Pleistocene Deposits at Kirwin, Phillips County, Kansas. JOHN C. FRYE and A. BYRON LEONARD. Pp. 29–48; pls. 3; figs. 3.

Ohio Department of Natural Resources—Columbus, 1953.

Inf. Circ. 3. Water Resources of Jackson County, Ohio. ALFRED C. WALKER. Pp. 15; pls. 8; tbls. 3.

Tech. Rept. 1. The Hydraulic Properties of a Dolomite Aquifer Underlying the Village of Ada, Ohio. WILLIAM C. WALTON. Pp. 31; figs. 20. *Results of aquifer test, October, 1952.*

North Dakota Geological Survey Circulars, Nos. 47–57. Summaries of the following wells: Hilda Johnson "A" No. 1; No. 1 Woodrow Starr; Martin A. Voeller No. 1; Herman May No. 1; Mueller No. 2; Edwin Werner No. 1; A. Payne No. 1; J. A. Fylken No. 1; Palmer H. Dilland No. 1; Carbonneau No. 1; Restad No. 1 Well.

Geology of the Pilot Mountain Area, Virginia. RICHARD V. DIETRICH. Pp. 32; pl. 1; figs. 16. Bull. of the Virginia Polytechnic Inst., Eng. Experiment Station, Ser. 91, Vol. 46, No. 4, Blacksburg, 1954. Price, 25 cts. *Stratigraphy, structure and economic geology of area. Includes geologic map, 1 inch to a mile.*

Analysis Directory of Canadian Coals. E. SWARTZMAN. Pp. 204. Canada Dept. of Mines, No. 836, Ottawa, 1953. Price, $2.50. *Second edition; includes analyses available to December, 1952.*

Preliminary Report on the Geology of the Emo Area, District of Rainy River. G. L. FLETCHER and T. N. IRVINE. Pp. 5. Ontario Dept. of Mines, P. R., 1952–3, Ottawa, 1954.

Graphic Problems in Petroleum Geology. L. W. LEROY and JULIAN W. LOW. Pp. 238; pl. 2; figs. 44. Harper & Bros., New York, 1954. Price, $4.50. *Excellent laboratory manual that includes 31 problems involving drafting, map construction, lithofacies studies, structural contour maps and interpretation of aerial photographs. An addition of a few problems in mining geology would have made this manual all inclusive in graphic problems in general geology.*

Introduction à la Lecture des Cartes Géologiques. A. BONTE. Pp. 277; pls. 8; figs. 103. Masson & Cie, Paris, 1953. Price, 1660 frs. *Second edition of a well-illustrated textbook describing principles of stratigraphy and structural geology, types of topographic and geologic maps, and graphic constructions of maps and sections.*

Congrès Géologique International—Alger, 1953.

Comptes Rendus de la Dix-neuvième Session, Alger, 1952.

Section I, Fasc. I. Les Subdivisions et les Corrélations de l'Antécambrien. Pp. 154. *15 papers on stratigraphic relations of the Precambrian in Scotland, Africa, Greenland and Brasil.*

Section II, Fasc. II. Le Paléozoique Nord-Africain et ses Corrélations avec Celui des Autres Régions du Monde. Pp. 188. *18 papers on Paleozoic stratigraphy in Africa, South America and southern Europe.*

Section III, Fasc. III. Mécanique de la Déformation des Roches: Influence sur les Conceptions Tectoniques. Pp. 243. *25 papers, including 3 abstracts, on interesting tectonic problems in many parts of the world.*

Section IV, Fasc. IV. Topographie Sous-Marine et Sedimentation Actuelle. Pp. 148. *Includes 16 papers, two on submarine canyon and others on recent sedimentation.*

Section V, Fasc. V. Les Prehominiens et les Hommes Fossiles. Pp. 378. *4 papers and 3 abstracts on studies of fossil man in Poland, Russia and Africa. Catologue of fossil man includes name of site, discoverer, remains, repository and bibliography.*

Section VIII, Fasc. VIII. L'Hydrogéologie des Régions Arides et Sub-Arides. Pp. 280. *22 short papers and 6 abstracts on ground-water resources in arid and semi-arid regions.*

Section X, Fasc. X. La Genèse des Gites de Fer. Pp. 185. *11 short papers on various types of sedimentary, metasomatic, and supergene iron deposits. 10 other papers in abstracts form only.*

Section XI, Fasc. XI. Origine des Gisements de Phosphates de Chaux. Pp. 197. *17 papers on mineralogy and formation of phosphate deposits. Areal reports include Africa, Mexico, Western United States, Florida, Israel, England and Europe.*

C.I.P.E.A., Fasc. XVIII. Comité International pour l'Étude des Argiles. *20 papers including ones on X-ray studies, standardization of differential thermal analysis, structures of various clay and mica minerals.*

Geological Survey of the Anglo-Egyptian Sudan Report for 1950–1952. GERALD ANDREW. Pp. 51. Sudan Government Geol. Survey, Khartoum, 1953. Price, P. T. 40 or 8/–. *Contains list of publications and reports.*

Statistical Summary of the Mineral Industry, 1946–1952. Pp. 351. Colonial Geol. Surveys, London, 1953. Price, 1.7s. 6d. net.

Annual Report of the Geological Survey Department for 1952. F. W. ROE. Pp. 134; pls. 20; figs. 18; tbls. 17. British Territories in Borneo, Kuching, Sarawak, 1954. Price, 7s.

Historique de l'établissement de l'échelle stratigraphique du Katanga. M. ROBERT. Pp. 15. Comité Spécial du Katanga, Pub. 23, Bruxelles, 1954.

Présence de formations d'âge miocène inférieur dans le fossé tectonique du Lac Albert et de la Basse Semliki (Congo Belge). A. T. HOPWOOD and J. LEPERSONNE. Annales de la Société Géologique de Belgique, Liège, 1953. Pp. 83–113; pls. 2; figs. 6.

Carte Géologique de la Nouvelle-Calédonie. PIERRE ROUTHIER. Pp. 21. Office de la Recherche Scientifique Outre-Mer, Paris, 1953. Price, 1,200 frs. *Brief description of geology of the area. Geologic map, 1:100,000.*

Zentralblatt für Mineralogie—Stuttgart, 1954.

Jahr. 1952, Heft 3. Kristallographie und Mineralogie. H. O'DANIEL. Pp. 287–407; I–CCXXIV.

Jahr. 1953, Heft 2. Kristallographie und Mineralogie. H. O'DANIEL. Pp. 89–176.

Zentralblatt für Geologie und Paläontologie—Stuttgart, 1954.

Jahr. 1953, Heft 1. Historische Geologie und Paläontologie. O. H. SCHINDEWOLF and M. SCHWARTZBACH. Pp. 1–324.

Jahr. 1953, Heft 2. Historische Geologie und Paläontologie. O. H. SCHINDEWOLF and M. SCHWARTZBACH. Pp. 325–356.

Jahr. 1953, Heft 2. Teil I. Allgemeine und Angewandte Geologie einschl. Lagerstättengeologie, Regionale Geologie. FR. LOTZE and M. SCHWARTZBACH. Pp. 165–350.

The Composition and Origin of the Antrim Laterites and Bauxites. V. A. EYLES. Pp. 90; pls. 2. Mem. Geol. Survey of Northern Ireland, Belfast, 1952. Price, 12s. 6d. net. *Discusses chemical changes in formation of laterites; X-ray determination, nature and paragenesis of minerals in laterites; effects of metamorphism on bauxite; and paragenesis of oxide and hydrated oxides of aluminum.*

Union of South Africa Department of Mines—Pretoria, 1953.

The Geology of the Area Around Lichtenburg. J. W. VON BACKSTRÖM, F. W. SCHUMANN, H. D. LE ROEX, L. E. KENT and A. L. DU TOIT. Pp. 70; pls. 7; figs. 8. Price, 7/6. *Description of stratigraphy, petrology, and economic geology. Geologic map 1:125,000.*

The Geology of the Merweville Area, Cape Province. P. J. ROSSOUW and J. DE VILLIERS. Pp. 78. Price, 10s. *Brief description of general geology. Geologic map 1:125,000.*

Bull. of the Geological Survey of Taiwan, No. 5. Pp. 116; pls. 4; figs. 36; tbls. 32. Geol. Survey of Taiwan, Taipei, Jan., 1954. **The Gneisses of Taiwan.** T. P. YEN. *Detailed descriptions of general features of paragneiss, orthogneiss and migmatite bodies, petrographic descriptions of 6 gneiss bodies.* **The Lower Oligocene Yuhangian Foraminiferal Faunule and its Stratigraphic Significance in Taiwan.** LI-SHO CHANG.

Ministerio de Minas e Hidrocarburos—Caracas, 1953–54.

Actividades Petroleras, Nos. 112–113. Pp. 48.

Actividades Petroleras, Nos. 114–115. Pp. 26.

Western Australia Geological Survey—Perth, 1953.

Bull. 107. The Geology of the Country about Coolgardie, Coolgardie Goldfields, W. A. Pt. I—Regional Geology. J. C. MCMATH. **Pt. II—Selected Mining Groups.** N. M. GRAY and H. J. WARD. Pp. 365; pls. 27; figs. 33. *Description of general geology, structure and economic geology of area and detailed descriptions of various mining groups.*

Bull. 107. Supplementary Atlas. The Geology of the Country about Coolgardie, Coolgardie Goldfields, W. A.

SCIENTIFIC NOTES AND NEWS

WALTER E. LEWIS, Chief of the U. S. Bureau of Mines, Mineral Survey Branch in Region V, has been visiting drilling operations on the Cuyuna range in Minnesota. The purpose of the current operations is to study manganese-bearing slates in the area north of Manganese, Minnesota.

HOWLAND BANCROFT and E. C. LARSON, mining consultants, have been inspecting uranium properties of the Minerals Engineering Company in Utah.

PARKE S. SNAVELY, JR., supervising geologist at the U. S. Geological Survey Fuels Branch in Oregon and Washington, has been promoted to the post of supervisor for the branch's Pacific Region. His new headquarters will be in Menlo Park, California.

JOHN K. GUSTAFSON, chief geologist, and J. W. BUFORD, coordinator of Canadian development, have been appointed vice-presidents of Hanna Coal and Ore Corporation.

VICTOR HOLLISTER, geologist for American Smelting and Refining Company's Northwest mining division in Wallace, Idaho, has joined the staff of the Northern Peru Mining and Smelting Company, a subsidiary of the American firm. He expects to be at the Peruvian operation for approximately two years.

NICARO NICKEL COMPANY, which is a Cuban subsidiary of Freeport Sulphur Company, and the National Lead Company's Cuban subsidiary have received go-ahead signals for increased production from the Office of Defense Mobilization. A certificate of necessity for $55,250,000 was issued by the ODM to the Freeport Company for its mining operations at Moa Bay, Cuba. Eighty percent was allowed for rapid tax amortization. The National Lead Company subsidiary, NICKEL PROCESSING COMPANY, has been allocated $43,000,000 by the ODM for operation of the government-owned plant at Nicaro, Cuba. Capacity will be increased by 75 percent, or 51,500,000 pounds annually, by the program.

JACK B. GRAHAM, formerly with the U. S. Geological Survey, Washington, D. C., has joined the staff of Leggette & Brashears, consulting ground-water geologists, New York.

ALBERT P. RUOTSALA has resigned his position as exploration geologist with Bear Creek Mining Co. to finish work toward an M.S. degree. He is at present teaching at Macalaster College, St. Paul.

NORMAN K. FLINT, professor at the University of Pittsburgh, has been nominated president of the Pittsburgh Geological Society.

FRANK A. AYER, international copper mining consultant, and WALTER H. SAMMIS, president of Ohio Edison Co., are the 1954 winners of the Egleston Medal, Columbia University's highest award for "distinguished engineering achievement."

A. JOSEPH YAEGER, JR., mining engineer with American Smelting & Refining Co., El Paso, Texas, is now with Asarco's Mexican mining department in Mexico City.

E. M. PARIS, U. S. Vanadium Company mining superintendent at Uravan, Colo., has been appointed manager of mines for the company's operations in Colorado and Utah.

THE COUNCIL OF THE INSTITUTION OF MINING AND METALLURGY, London, announce the following awards: *The Gold Medal of the Institution* has been awarded to Mr. ESSINGTON LEWIS, president of the Fifth Empire Mining and Metallurgical Congress, in recognition of his long and distinguished services to the Mining and Metallurgical Industries of Australia; *Honorary Membership of the Institution* has been conferred on Mr. THOMAS PRYOR, past president, in recognition of his services to the Institution and to mining education; *The Consclidated Gold Fields of South Africa, Ltd. Gold Medal* for 1953 has been awarded to Dr. JOHN STUART WEBB for his work on the development of geochemical prospecting methods; *The Consolidated Gold Fields of South Africa, Ltd. Premium of Forty Guineas* for 1953 has been awarded to Mr. RALPH DANIEL for his paper entitled "Diamond mining practice in Kimberly, South Africa" (Trans. vol. 62); *The 'Arthur Claudet' Student's Prize* for 1953 has been awarded to THOMAS ANDREW HENDERSON for his part authorship of the paper entitled "Some exploratory experiments on the formation and control of magnetite during copper smelting operations" (Trans. vol. 62); *The 'William Frecheville' Student's Prize* for 1953 has been awarded to CYRIL LIONEL HALL for his part authorship of the paper entitled "Laboratory tests on the concentration of witherite from the Northern Pennines by froth flotation" (Trans. vol. 62).

WILSON D. MICHELL, geologist, Reynolds Metals Company, has been transferred to be in charge of the Geological Division's exploration program in the Guianas. He may be addressed at Box 896, Paramaribo, Surinam.

The Board of Directors of the AMERICAN GEOLOGICAL INSTITUTE, meeting at St. Louis on April 11, unanimously approved the plan to enlarge the NEWSLETTER and send it to every member of the profession. The general plan is outlined in the April issue of the NEWSLETTER. Beginning with the September issue, the NEWSLETTER will be sent to every person who is registered in the National Roster of Scientific and Technical Personnel (Earth Sciences). The address list for the NEWSLETTER is being compiled from the register. There are more than 12,000 in hand but there is reason to believe that about 5,000 are missing. Individuals who have not returned their AGI Roster Questionnaires should do so if they wish to receive Volume VI of the NEWSLETTER. Those who too hastily dropped their questionnaires in the well known circular file, or otherwise misplaced them, can obtain another copy by writing to the Institute.

W. F. JAMES, consulting geologist, Toronto, and advisor to the government on atomic energy, and J. SATTERLY, geologist, Ontario Department of Mines, have been elected Fellows of the Royal Society of Canada.

RALPH D. PARKER has been appointed General Manager of Canadian Operations for the International Nickel Company of Canada, Ltd., of which he is Assistant Vice-President.

A. W. MULLAN, JR., formerly geologist for the Dominion Gulf Company, Ltd., has joined the staff of McPhar Geophysics, Ltd., Toronto, as a field geologist.

JOHN C. FRYE, director of the State Geological Survey at the University of Kansas, has been named chief of the State Geological Survey for Illinois. He takes over his post as head of the largest state geological agency in the nation on July 1.

R. H. B. JONES, consulting geologist for Oliver Iron Mining Division in Duluth, Minnesota, is now staff geologist for U. S. Steel Corporation's Columbia-Geneva Steel Division.

J. M. B. GIBBONS, British mica expert, is serving as an advisor to the Australian government in the development, preparation and marketing of its mica fields.

SIR LEWIS FERMOR, former Associate Editor of this *Journal*, died on May 24 at his home near Woking, Surrey. He was 73.

HERBERT R. RICE, former editor of the Canadian Mining Journal, has been appointed professor of Mining Engineering and head of the department, University of Toronto.

L. M. SCOFIELD, Duluth, geologist with Pickands, Mather & Co., has resigned to open a consulting office in Duluth.

JOHN K. GUSTAFSON, chief geologist, and J. W. BUFORD, coordinator of Canadian Development, have been appointed vice-presidents of the Hanna Coal & Ore Corp.

ROBERT H. LANE of the engineering department, International Minerals & Chemical Corp., Carlsbad, N. M., has been advanced to geologist.

KIRTLEY F. MATHER, professor of geology and curator of the Geological Museum, and RUSSELL GIBSON, associate professor of economic geology, retired from Harvard University at the end of this academic year.

ANDREW V. CORRY, Minerals Attaché, U. S. Embassy, New Delhi, India, has completed his tour of duty. His successor will be FRANKE E. NOE, JR., now with the U. S. Embassy in Mexico City.

R. MAURICE TRIPP has resigned as an officer of Research, Inc., Dallas, in order to devote more time to the scientific development of mineral exploration. He will continue with the company as a consultant.

IRA B. JORALEMON and PETER JORALEMON are now associated as consulting mining engineers and geologists at 316 Montgomery Street, San Francisco 4.

ANTON GRAY resigned for reasons of health from Kennecott Copper Corp., effective July 1st, and took up residence in England in August.

VICTOR HODGSON has left the Buchans Company to take up employment in Cyprus.

R. J. MACNEIL, chief geologist for the Newfoundland and Labrador Corp., Ltd., has been promoted to vice-president and director of the Corporation.

BENO GUTENBERG, professor of geophysics and director of the Seismological Laboratory of the California Institute of Technology, has been elected a foreign member of the Geological Society of London.

THE GEORGIA INSTITUTE OF TECHNOLOGY recently established an undergraduate curriculum leading to the Bachelor of Science degree in Physics, *Geophysics Option*.

MORRIS F. LACROIX, a senior partner of Paine, Webber, Jackson & Curtis and president of Copper Range Co., was awarded an honorary degree of Doctor of Engineering from Michigan College of Mining and Technology last June.

SOUTHWEST RESEARCH INSTITUTE has announced the forthcoming publication of a comprehensive and continuing inventory of economic resources relating to the sound industrial development of Texas and adjoining Southwestern states, to be entitled the Southwestern Resources Handbook.

EVAN JUST, vice-president of Cyprus Mines Corp. of New York, was the commencement speaker at the 54th annual commencement of the Montana School of Mines.

JUDSON L. ANDERSON, geologist specializing in gas and oil reserves estimates, has joined the Columbia Gas System as an assistant to Irving K. Peck, vice-president, Houston, Texas.

ROBERT S. MOEHLMAN, of the Austral Oil Exploration Co., who has been vice-president and a member of the Board of Directors, has been elected to the newly created office of Executive Vice-President. Prior to his association with Austral, Moehlman was chief geologist for South American Mines Co. JAMES H. McGUIRT, who has been chief geologist for the company since early 1951, has been elected vice-president.

THE GEOLOGICAL SURVEY OF CANADA placed 86 parties in the field this year.

A. E. J. ENGEL has been promoted from associate professor of geology to full professor at the California Institute of Technology.

WILLIAM T. HOLSER, until recently assistant professor of geology at Cornell University, has accepted a position as principal geochemist in the Structural Chemistry Division at Battelle Memorial Institute, Columbus, Ohio. He will start a new program of experimental mineralogy for the Institute, which serves industry and the government as a non-profit research organization.